ARMY RESEARCH LABORATORY

Evaluation Strategies for Live-Fire Planning, Analysis, and Testing

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Abstract

As a result of recommendations made by the National Research Council to Mr. C. Adolph, OSD Director, Test and Evaluation (DT&E), in a report, "Vulnerability Assessment of Aircraft-A Review of the DOD LFT&E Program," January 1993, an effort was launched to improve the live fire test (LFT) waiver process through development of a methodology to quantify advantages and disadvantages of full-scale, full-up test programs. Mr. Walter Hollis, the Army Deputy Under Secretary for Operations Research (DUSA[OR]), tasked the U.S. Army Materiel Systems Analysis Activity (AMSAA) and U.S. Army Research Laboratory (ARL) to develop the Live Fire Vulnerability/Lethality Risk-Benefit Assessment Methodology. ARL (Deitz et al.) was chosen to lead this effort and AMSAA (LaGrange et al.) was to provide support. On 22 Mar 93, the set of proposed deliverables was accepted by Mr. Adolph and the Senior Test and Evaluation Group. This report presents a history and summarizes work done by the group. Section 2 discusses in detail the V/L process and methodology and models used in V/L assessments. Section 3 examines the connection of damage-to-engineering operations to processes different from standard V/L analyses. Section 4 discusses the type of survivability/vulnerability information that must be developed during various phases of the acquisition cycle. Section 5 discusses four methodologies that could be applied to assess the cost-benefit LFT. Section 6 summarizes conclusions and recommendations. Appendices A-D provide details on the supporting theorems of section 4.

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1. INTRODUCTION

1.1 <u>Background</u>. In 1991, Mr. Charles Adolph, Director, Test and Evaluation (T&E), Office of the Secretary of Defense (OSD), tasked the National Research Council (NRC) to review the Department of Defense (DOD) Live-Fire Test and Evaluation (LFT&E) Program. Specifically, NRC was asked to review several methodologies, such as computer modeling, engineering analysis, and live-fire testing (LFT), and identify and evaluate the costs and effectiveness of these methodologies and identify deficiencies. Recommendations were requested. NRC completed their review in late 1992, and their findings and recommendations were published in January 1993 in a report entitled "Vulnerability Assessment of Aircraft - A Review of the DOD LFT&E Program."

LFT legislation requires full-up LFT for covered systems, unless a waiver of full-up LFT is requested before Milestone II (MS II). If a waiver of full-up LFT is requested, it must include plans for assessing the vulnerability/lethality (V/L) of the covered system and the waiver must show why full-up LFT would be "unreasonably expensive and impractical." The waiver must include "a report explaining how the Secretary plans to evaluate the survivability or the lethality of the system or program and assessing possible alternatives to realistic survivability testing of the system or program." The LFT law states that a covered system should be subjected to threat weapons "likely to be encountered in combat."

The NRC report questioned the adequacy of the 1988 LFT&E guidelines, which were published by OSD. NRC stated that the waiver process was not understood by the field and that OSD was not strictly enforcing the full-up LFT waiver process. The NRC concluded that no covered system had ever undergone full-up LFT and that no system had ever requested a waiver from full-up LFT. The 1988 OSD LFT&E guidelines do not stress the need to request a waiver from full-up LFT (when less than full-up testing is planned) but imply that other methods of testing and analysis can satisfy the LFT legislative requirements (without having to formally request a waiver). The NRC report concluded that the field did not understand the LFT waiver process and that systems managers were reluctant to request a waiver for fear that it would "stigmatize" their programs. Also, there was a general lack of understanding as to what constituted realistic survivability testing (especially as it related to threat weapons expected to be encountered in combat).

The conclusions section of the NRC report states that "the committee believes that the 1987 Congressional LFT law mandates LFT of full-scale, full-up aircraft, including onboard ordnance, unless

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a waiver is granted by the Secretary of Defense." The committee also concluded "that a waiver is required to omit the full-scale, full-up tests."

One of the recommendations made by the NRC was that "the T&E Director formalize the LFT waiver process by developing a risk-benefit assessment methodology that can be used uniformly to determine whether a full-scale, full-up test program for any particular aircraft is "unreasonably expensive and impractical." The methodology must also apply to the evaluation of the alternate LFT program for the subscale targets." Mr. Charles Adolph accepted this NRC recommendation and on 27 January 1993 prepared a memorandum to the Senior T&E Group requesting the development of a risk-benefit assessment methodology to be applied uniformly when deciding whether full-scale, system-level testing is "unreasonably expensive and impractical," and a formalized waiver process that supports this methodology.

An OSD "Committee on Vulnerability Guidelines (CVG)" was formed to address the issues raised by Mr. Adolph. The committee is chaired by Dr. Al Rainis (Tactical Systems/OSD[A]) and has membership from each of the services, from SDIO, and from the office of Mr. O'Bryon, Deputy Director, T&E, Land & Maritime Systems (DT&E/LMS), and Mr. Ledesma, Deputy Director, T&E, Air & Space Program (DT&E/ASP). Dr. Rainis met with Mr. Adolph's Senior T&E Group in early February 1993 and was tasked to prepare a Scope-of-Work (SOW) to develop the "risk/benefit assessment methodology." The CVG prepared the Risk/Benefit SOW and briefed it to the Senior T&E Group on 24 February 1993. The Army member on the Senior T&E Group, Mr. Walter Hollis, the Deputy Under Secretary for Army Operations Research (DUSA[OR]) and Army member of Mr. Charles Adolph's Senior T&E Group, felt that no contractor had the necessary LFT experience and expertise to perform this effort and recommended that the task be assigned to the Army. The Senior T&E Group concurred with this approach and on 26 February 1993 Mr. Hollis tasked the U.S. Army Materiel Systems Analysis Activity (AMSAA) and the U.S. Army Research Laboratory (ARL) to develop the "Live-Fire (LF) V/L Risk-Benefit Assessment Methodology." A draft SOW was provided that contained the background, technical requirements, and schedule.

Following discussions between Mr. Myers (Director, AMSAA) and Mr. Vitali (Director, ARL), it was agreed that ARL (Dr. Deitz et al.) would take the lead on this effort and AMSAA (Mr. LaGrange et al.) would provide support.

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The risk-benefit assessment methodology SOW contained the following tasks:

(1) The contracted agency shall conduct a technical analysis and develop a risk-benefit assessment methodology, initially to address each of the three basic categories of weapon systems, namely, aircraft, ships, and land platforms, which quantifies the benefits associated with full-up, system-level live-fire V/L tests, the risks associated with waiving these tests, plus the risk-benefit of implementing each of the following alternatives:

- No testing or minor testing of components only.

- Live-fire V/L testing of major subassemblies and assemblies only.

- Live-fire V/L testing of the total system only.

- Live-fire V/L testing of the total system with testing of major subassemblies and assemblies.

(2) The technical analysis shall consider, time permitting, the effectiveness of existing vulnerability analysis methods used by each of the Services' development agencies and how these methods should contribute to the risk-benefit-cost balance assessment methodology.

(3) The methodology shall consider the likelihood of an undetected vulnerability and compare the risk-cost-payoff of the different alternatives, described previously, with the likelihood of detecting a vulnerability for which a cost-effective fix would be practical. In developing the methodology, the contracted agency shall include considerations of the susceptibility (probability of hit) of the system, and test facility capabilities.

(4) The methodology shall also address the risk-cost-payoff to the system acquisition strategy related to the alternatives, listed previously, when fixes/design changes are required. Further, the contracted agency shall include a determination of the usefulness and applicability of transfer of data from other relevant test programs.

(5) The contracted agency shall provide a "best effort" to include in the methodology the benefits of those unquantifiables not specifically listed in the previous approaches.

(6) Based on the previous analysis, the contracted agency shall develop risk-benefit assessment methodologies applicable to the three basic categories of weapon systems, and, if possible, combine them into a single risk-benefit assessment methodology that can be applied to all classes of weapon systems.

1.2 Approach. On 1 March 1993, ARL responded to the Mr. Walter Hollis task and agreed to take the lead in developing a "Live Fire V/L Risk-Benefit Assessment Methodology" and AMSAA agreed to provide support. On 4 March 1993, Dr. Deitz (ARL) and Mr. LaGrange (AMSAA) met separately with Dr. Al Rainis and Mr. Walter Hollis. Dr. Rainis and Mr. Hollis provided guidance regarding the scope and schedule for developing the LFT V/L Risk-Benefit Methodology. It was agreed that a final draft report would be prepared by the end of July 1993 and that progress briefings would be provided to Mr. Adolph's Senior T&E Group when requested.

On 9 March 1993, Mr. LaGrange and Dr. Deitz provided a background briefing to AMSAA management and outlined the approach to be taken on this study. On 16 March 1993, Dr. Deitz and Mr. LaGrange briefed the planned approach to the tri-service CVG group headed by Dr. Rainis. On 19 March 1993, ARL and AMSAA management was given a pre-brief of the planned study approach.

On 22 March 1993, the ARL/AMSAA "Live-Fire V/L Risk-Benefit Methodology" was briefed to Mr. Charles Adolph and the Senior T&E Group. This briefing reviewed the statement of work, discussed a top-down and bottom-up approach to V/L assessment, and proposed a set of deliverables that would result from this study. The set of deliverables focuses on the following four areas:

(1) Describe the V/L process (V/L taxonomy), particularly Levels 1 through 3, discussing how testing and modeling measures must be comparable to have utility and how the mapping operations affect the fidelity of the predicted measures.

(2) Document the building-block process so as to reflect the full gamut of tests/models/decision processes to provide an acceptable basis for the LF assessment process. For each element/task of the process, provide a description of required standards and practices to ensure adequate fidelity. Examine the applicability of the process for a range of target classes and weapons programs.

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(3) Investigate the nature of various specific cost/risk/benefit measures. Identify which might have promising utility. Develop various methods (either by sampling statistics or heuristic approaches) to relate data/process uncertainties to downstream measures. This effort should include the development of a specific decision process, applicable at Acquisition MS II, which will aid/assist/illuminate the risk/benefit factors involved in the decision whether or not to request a final (or conditional) waiver for combat-configured LFT.

(4) Use the V/L process (of Effort 1) to show the connectivity of Damage-to-Engineering Operations among: (a) the LF assessment process, (b) the battle damage assessment and repair (BDAR) process, (c) the reliability, availability, and maintainability (RAM) process, and (d) the operational and developmental test processes.

This generalized approach was accepted by Mr. Adolph's Senior T&E group.

The next five sections summarize the work performed in each of the four areas. Section 2 presents in detail the V/L taxonomy and the methodology and models used to do V/L assessments. Section 3 examines the connectivity of damage-to-engineering operations with processes different from standard V/L analyses. Section 4 discusses the type of survivability and vulnerability information that must be developed during various phases of the acquisition cycle. Section 5 discusses four methodologies that could be applied to assess the cost benefits of doing full-up LFT (and the risks of not doing full-up LFT). Section 6 summarizes conclusions and recommendations. In addition, Appendices A–C provide details on the supporting theorems of section 4.

2. V/L PROCESS

To understand the nature of V/L assessment of targets, it is critical to understand the framework within which all assessments for the past 40 years have taken place. This framework is not just implicit to computer-based assessments but provides a key link to field observables as well. The vulnerability process can be thought of as a transformation of information among four levels.

2.1 V/L Spaces, Mappings, and Modeling.

2.1.1 Basic Definitions[*] of Lethality, Vulnerability, and Survivability.

Vulnerability: The characteristics of a system that cause it to suffer a degradation (loss or reduction of capability to perform the designated mission[s]) as a result of having been subjected to a hostile environment on the battlefield.

Lethality: The ability of a system to cause the loss of, or a degradation in, the ability of a target system to complete its designated mission(s).

Survivability: The capability of a system (resulting from the synergism among personnel, materiel, design, tactics, and doctrine) to avoid, withstand, or recover in hostile (man-made and natural) environments without suffering an abortive impairment of its ability to accomplish its designated mission. If the two facets under control of a weapons designer, materiel and design, are lumped into System Characteristics, and the effects of personnel are distributed appropriately over the three remaining variables of Characteristics, Tactics, and Doctrine, then survivability can be written functionally as:

$$SURV = f \{ \text{Threat (Char, Tactics, Doc)},$$
$$\text{Battlefield Environment},$$
$$\text{System (Char, Tactics, Doc)} \}.$$

2.1.2 V/L Taxonomy.
Insight into these definitions can be gained through use of what is now called the *V/L Taxonomy*. It was first generated (Deitz and Ozolins 1988) as a by-product of a program to improve the quality of LF vulnerability modeling. In essence, the taxonomy provides a method to decompose the elements of V/L into a sequence of simpler constituent parts. As we will see, the parts relate to each other in a specific processing order, but are fundamentally different, one from the other, and each has its unique and appropriate use in the general scheme of V/L assessment.

2.1.2.1 V/L Taxonomy via a Combat Analogue.
The taxonomy can probably best be introduced via a description in terms of its physical and engineering processes. Figure 1 illustrates such a view of the taxonomy. The so-called process structure is illustrated with a missile attacking an aircraft, although

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[*] Consistent with DODI 5000.2, <u>Defense Acquisition Management Policies and Procedures</u>, 23 February 1991.

Level - Descriptor

Level 0] Threat - Launch Initial Conditions

Level 1] Threat - Target Interaction Initial Conditions

Level 2] Target Damaged Components

Level 3] Target Measures-of-Capability

30 40 50 Climbing 30 40 50
20   60   Rate: 20   60
10   70   10   70
Before   After:

Operational Test/ War

Level 4] Target Measures-of-Effectiveness (Utility)

Transformations

Threat Propagation to Threat/Target Interaction Initial Conditions

Threat/Target Interaction Initial Conditions to Damaged Components

Damaged Components to Reduced Capability

Reduced Capability to Reduced Battlefield Utility

Figure 1.   The V/L taxonomy illustrated with physical and engineering processes in the center column. Levels 0–4 are described on the left. The transformation processes between the levels are described on the right.

this process is applicable for any ballistic threat against any target.[*] The cartoons at the center of Figure 1 alternately represent the levels, indicated on the left, and the transformation processes, indicated on the right.

We start with an explanation of the process of vulnerability using Figure 1. In conventional vulnerability, it is normal practice to assume a warhead hit (or ballistic interaction) with a target *as a given*. It is useful to think in this context of an LF test. Level 1 represents a complete geometric and material description of a threat (here a missile), a target (here an aircraft), and the relevant kinematics as the two just begin to interact. The event may be signaled by the instant an unguided bullet begins to collide with a target or, as implied by the illustration, a fuze triggers an explosive mechanism in the vicinity of the target. The process of an LF test is to transform an undamaged target at Level 1 to a damaged target at Level 2. The transformation process is the LF event itself and is characterized by all the physical mechanisms of destruction. They may include main penetrators, fragments, blast, shock, fire, fumes, and even synergistic effects. As a consequence of the LF transformation event, target damage may have occurred at Level 2. We choose to think of Level 2 as characterized by a list of killed components; sometimes this is called a damage vector.

A target that has received damage may likely not continue to operate as before damage. In the case of a damaged aircraft illustrated here, parts of the control surfaces may be removed, hydraulic lines severed, and electronic boxes impaired. In a test which might be performed, the rate of climb might be measured to see how this key capability property may have been reduced. The capability test is the transformation process, which takes target damage at Level 2 and transforms it to reduced capability at Level 3. The transformation from Level 2 to Level 3 can be thought of as characterized by engineering relations. It is important to note that the metrics of Level 1, threat/target initial conditions, Level 2, damaged components, and Level 3, measures of capability, are all measurable and objective. A methodology that predicts tire inflation levels as a function of time and damage that can then be combined with scenario requirements to determine effectiveness is given in Grote, Moss, and Davisson (1996).

The capability state of Level 3 should be characterized by all capability measures which cause a military platform to have military utility or worth in a particular mission. For example, if the platform can move, the metrics might include measures of speed and agility. If the platform has a gun, the metrics might include time to acquire a target, rate of fire, and hit dispersion.

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[*] It will be noted later that this applied as well to nonballistic threats such as directed energy and chemical weapons analyses.

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The final transformation occurs as a platform with reduced measures-of-capability is exercised in a particular mission scenario. If the particular reduced measures-of-capability are unimportant to the mission at hand, then the utility of the platform may remain high. If not, the utility may be reduced, even drop to zero. The notion of measures-of-effectives or utility is illustrated as a Level 4 metric and would be reached through an operational test or war experience. Given the complexity of this transformation and the lack of real-world repeatability, we claim that Level 4 metrics are essentially not observable, but rather must be inferred through war games or developed via subjective processes.

One of the key insights provided by taxonomy is that the discipline of vulnerability ranges over three distinct kinds of metrics, damage, capability, and utility, and great care must be exercised to see that these metrics are not confused, incorrectly calculated, or improperly applied.

In contrast to vulnerability, in which a threat interaction with a target is normally assumed, lethality includes the process of getting the threat to the target. Thus Figure 1 includes a Level 0, which represents the initial conditions for the launch of the threat. The transformation of the threat at Level 0 to the arrival at the target (Level 1) would occur here as the firing of the missile. In a set of repeated experiments, a distribution of threat arrival conditions could be generated. One particular condition at a time might be chosen to use for a given initial threat-target interaction at Level 1.

2.1.2.2 V/L Taxonomy via a Mapping Abstraction. The taxonomy is useful in developing the mathematical abstractions needed for V/L modeling. Each of the levels of the process can be thought of as a mathematical space. As illustrated in Figure 2, the cartoons in the middle of Figure 1 describing the levels have been replaced with ellipses representing these spaces. The information at Levels 0–4 can each be described by vectors within these spaces, here represented as bullets; however, the properties of the vectors are completely different from one space to the next. As mentioned previously, the metrics of damage, performance, and utility are not interchangeable.

As noted previously, an LF test can be thought of as a mapping from Level 1 to Level 2. If the LF shot were repeated, it is likely that random physical processes could lead to a different damage vector; thus a different vector would result. LF tests and modeling efforts have shown (Deitz and Ozolins 1988) that the outcome for many LF tests can exceed 10^6 individual damage vectors. The high dimensionality of Level 2 space is at the core of the difficulty in validating V/L models.

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Level - Descriptor   **Transformations**

**Level 0] Threat - Launch
            Initial Conditions**

$O_{0,1}$ Mapping *via*
            Physics

**Threat Propagation to
Threat/Target Interaction
Initial Conditions**

**Level 1] Threat - Target
            Interaction
            Initial Conditions**

$O_{1,2}$ Mapping *via*
            Physics

**Threat/Target Interaction
Initial Conditions to
Damaged Components**

**Level 2]   Target
            Damaged
            Components**

$O_{2,3}$ Mapping *via*
            Engineering

**Damaged Components to
Reduced Capability**

**Level 3]   Target
            Measures-of-
            Capability**

$O_{3,4}$ Mapping *via*
            Operations Research

**Reduced Performance to
Reduced Battlefield Utility**

**Level 4]   Target
            Measures-of-
            Effectiveness
            (Utility)**

Figure 2. The V/L taxonomy illustrated via a mapping abstraction. The ellipses in the middle column represent mathematical spaces. The points contained within represent vectors. The arrows represent mapping operators, which take a vector at one level and perform a mapping to the next lower level.

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The transformation processes listed at the right of Figure 1 have been reproduced in Figure 2 as well. It is useful to think of the transformations as mathematical operators. These operators operate on information on one level to yield information at the next. A nomenclature that has been adopted is to use a capital O (for operator), followed by subscripts indicating the input and output levels. Thus the $O_{0,1}$ Operator represents the mapping of the threat from launch to the arrival at the target. The $O_{1,2}$ Operator represents the damage mapping process of an LF test. The $O_{2,3}$ Operator represents the transformation to reduced capability of a target following damage. And the $O_{3,4}$ Operator represents the transformation from reduced capability to military utility for a particular mission profile.

2.1.2.3 Insights Provided by the V/L Taxonomy. There are a number of important aspects of the taxonomy, particularly for understanding the definitions for vulnerability, lethality, and survivability.

(1) The V/L metrics associated with each of the Levels 0–4 are fundamentally distinct. That is to say, component damage across a weapon platform is different from potentially diminished capability of the platform and both are different from the possible reduction in military utility of the platform. Both vulnerability of a platform or the lethality of a weapon can be defined in any combination of metrics from Levels 2, 3, and/or 4.

(2) The five levels are sequential, independent, and nonpermutable.

(3) Modern V/L modeling schemes must track the taxonomy so that Levels 2 and 3 metrics can be compared with the results of field tests.

(4) The operators are generally stochastic, nonlinear, and noninvertible; therefore, multiple levels (e.g., Levels 2–4) cannot be properly mapped in a single process.

(5) In certain V/L modeling tasks, the mathematical mapping operators must use stochastic processes to yield accurate results. This is most notably true in the damage operator, $O_{1,2}$, where simplifications using expected-value transformations have been shown to yield incorrect results.

(6) Level 4 metrics, essentially battlefield utilities, cannot be observed through testing.

2.1.2.4 Taxonomy and Survivability. A number of times we have emphasized the importance of not confounding the different kinds of V/L metrics associated with Levels 2, 3, and 4. The data associated with a Level 2 metric is straightforward—it is simply an accounting of damaged or killed components. At Level 3, the metrics are capability. Capability measures can be defined clearly in terms of measurables such as top speed, minimum speed, rate of acceleration, rate of fire, etc. Level 4 metrics may best be thought of as utilities and therefore dimensionless. At Level 4, however, the metrics become whatever the modeler may mean them to be, or even something else.

It may be helpful to review a hypothetical example of an aircraft performing a military mission. With a view to Figure 1, let us assume that a missile attack has led to severing a fuel line to one of two engines on the aircraft. The damage vector at Level 2 is damage vector of one element, one killed fuel line. Applying the capability operator $O_{2,3}$ to the damage vector gives the following result at Level 3; the aircraft is able to fly straight and level, but not climb. Now we examine the Military Utility Operator, $O_{3,4}$. To apply this operator, a number of missions must be defined. In one mission, it might be necessary to climb rapidly to avoid ground ordnance. In mission two, it might only be necessary to maintain level flight. Thus we could define two $O_{3,4}$ mapping operators. In the case of the first, the damaged aircraft could not fulfill the mission and would have a utility of zero. In the case of the second mission, the mission could be supported, giving a utility of one. One can envision missions which when applied against partially performing platforms would result in partial utility $(0.0 < U < 1.0)$. Given some set of mission utilities, it is then possible to develop an expected utility, averaged over some set of missions.

Often utilities, averaged or otherwise, are used by the community of war games. The utilities are often simply *defined* to be probabilities of a certain class of kill. The utility, on the same interval as a probability, is used in the war game to make a draw, assuming a ballistic encounter. Based on the outcome, the platform may be removed from the conflict. Potentially three errors are committed by this practice.

(1) Binning a vulnerability metric in a war game scenario which has already been binned by a vulnerability analyst: The war gamer should take the capability information from Level 3 and play that characterization of the platform in his mission encounter. The war game will then *define* the utility of the (damaged) platform.

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(2) Averaging two or more utilities: Often averages are performed over the outcomes of multiple binning processes. This is legitimate mathematically. However, a major problem occurs when an average utility is applied to a specific mission. They may, in fact, be very different numbers.

(3) Turning a utility into a probability: A practice which has seen widespread use in the ground arena has been to argue that an average battlefield utility is equivalent to the probability of total loss of the modeled capability.

This third practice has been shown wanting for many years (Rapp 1983 and Starks 1991), but the numbers provided by the V/L community to its customers are still referred to as "probabilities of kill" or "expected loss of function (LOF)," even if at their foundation, they may suffer from some or all of these three serious problems.

Finally, if a series of utilities are derived as a function of ballistic threats introduced at Level 1 and played against a number of missions in the $O_{3,4}$ utility mapping, it would appear that we have proper measures for what might be called *ballistic survivability*. We have ignored all other factors in survivability including the probability of detection at various wavelengths, agility, etc. One can think of *overall survivability* as the combined output of an $O_{3,4}$ utility map, using not only the Level 3 capability metrics of ballistic measures but also the similar capability metrics from all of the other disciplines which affect survivability. Further discussion of the live fire taxonomy application is found in Deitz (1996).

2.2 Army V/L Modeling. By nature, LFTs are empirical. Therefore, it is paramount that the V/L model used for simulation be capable of estimating the probability of occurrence of any particular empirical test result. Furthermore, it is important that the model be capable of calculating data in all of the four V/L spaces. Unfortunately, many models give deterministic results and cannot produce information in the four V/L spaces.

Two Army deterministic models have been used in the past: Vulnerability Analysis Methodology Program (VAMP) and Vulnerability Analysis for Surface Targets (VAST). The LOF and component probability of kills[*] generated by these models are expected values. The results of any particular

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[*] Note that VAMP is only capable of producing LOFs.

empirical test may or may not match these expected values. Thus it is necessary to use a model that generates entire distributions of target LOFs and damage vectors, allowing the estimation of the probability of occurrence of any particular empirical test result. The current Army model used for simulating LFT&E for land vehicles is called the Stochastic Quantitative Analysis of System Hierarchies (SQuASH).

2.2.1 The Army's SQuASH Model. The SQuASH model (Ozolins 1988; Deitz and Ozolins 1989) uses repeated sampling of random variables to provide highly detailed predictions. A distribution of damage vectors where each vector describes the functional/nonfunctional state of every critical vehicle component is computed by repeatedly simulating the threat impact. Component damage vectors are the only necessary and sufficient measure for analytically verifying agreement between a model and an LFT. Estimates for the probability of occurrence of a particular target-threat interaction (Space 2 outcome) can be computed from the predicted distribution of damage vectors. By incorporating the degraded states vulnerability methodology (DSVM), SQuASH has the ability to measure capability degradation in terms of capability categories (Space 3). The SQuASH model can also derive the vehicle LOFs distributions and probability of catastrophic kill. Thus, in the spaces framework, SQuASH can perform the Space 1 to 2 mapping (physics), the Space 2 to 3 mapping (engineering capability), and the Space 3 to 4 mapping (battlefield conditions/doctrine).

Inputs to SQuASH are numerous, covering the initial conditions in Space 1 to algorithms for $O_{1,2}$, $O_{2,3}$, and $O_{3,4}$ mappings. Inputs include a detailed three-dimensional geometric characterization of the target (e.g., components, spatial location of components, component properties, etc.), threat information (e.g., shaped-charge [SC] warhead/jet performance, residual penetration capabilities), the threat's impact location(s) (either a specific location or a set of Monte Carlo impact locations for a full view), spall inputs (e.g., the expected number of lethal fragments), the critical component probability functions of a kill given a hit, deactivation diagrams, and DSVM fault trees.

All critical components as well as noncritical components capable of producing spall or shielding spall must be geometrically modeled to accurately predict LFT observables. Deactivation diagrams from the criticality analysis must also be specified. In the case of SQuASH code using the DSVM, a set of DSVM fault trees are used to define critical components and their relationship to each of the capability categories.

Monte Carlo simulations are performed for each target-threat interaction (i.e., LFT shot). Monte Carlo sampling is used for the following random variables:

- The threat's impact location on the target.

- The penetration capability of a kinetic energy (KE) munition on initial target impacts.

- The residual KE penetration ability.

- The initial penetration depth of an SC jet.

- The spatial characterization of spall.

- The number of lethal spall fragments.

- A kill/no-kill assessment of a critical component from the effects of the main KE penetrator, KE penetrator fragment(s), or an SC jet.

- The effects of the number of spall fragments impacting the component.

SQuASH output for repeated sampling at a given threat impact location includes the distribution of damage vectors (representing the functional/nonfunctional capabilities of all critical components), the probabilities of perforating armor, the distribution of residual penetration, and the probabilities of kill for individual components. The SQuASH analysis may also include the distribution of mobility LOFs, the distribution of firepower LOFs, and the distribution of vehicle probability of catastrophic kills. Figure 3 illustrates SQuASH in the space framework.

2.3 The Testing Process. Models and analysis methods that are to be applied in support of LFT (premilestone [PMS] II) should include information at all stages at which the vulnerability of the system can be affected. Thus, for each threat damage mechanism, a complete set of vulnerability information includes component vulnerability data, subsystem-component interactions (fault trees), and subsystem interactions. Additionally, if damage mechanisms are not independent, combined effects for components, subsystems, and multiple subsystems must be included. For whatever type of model is applied, it is

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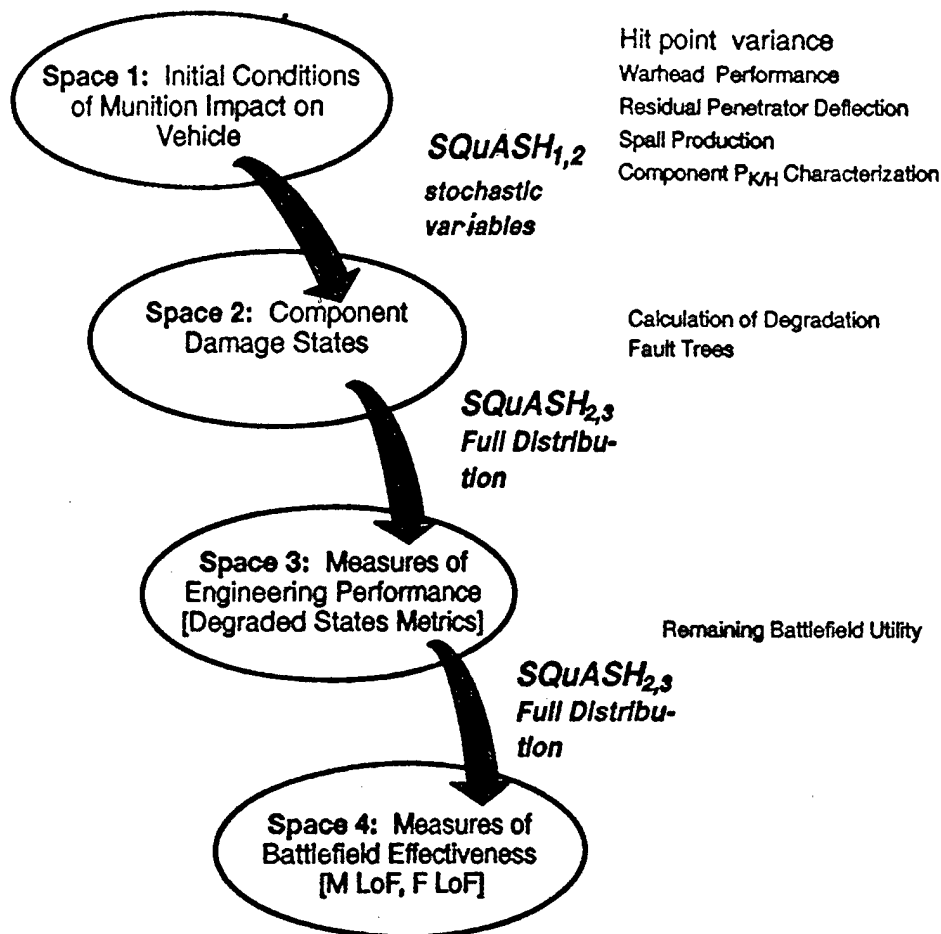
Figure 3. Spaces of vulnerability analysis—SQuASH model.

reasonable to assume an uncertainty for each stage of input as well as an uncertainty each time the model aggregates damage among components, within subsystems, and between subsystems (to the system level). The uncertainty associated with aggregation is due to possible dependent effects among various components and subsystems or among various damage mechanisms or both.

The tradeoffs between full-up LFT and other information-gathering plans must address the ability to obtain information at each of these stages. Component testing provides only component vulnerability data with no information on interaction of components. Subsystem testing can provide information on both individual components and synergistic effects on interdependent components, but provides no information

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on synergistic effects of multiple subsystems (e.g., fire initiation due to interaction of sparking from electrical components and leakage of fuel or hydraulic fluid). Multiple subsystem tests can provide data on individual components, subsystems, and interaction of the subsystems tested. Each of these kinds of test are usually designed to investigate specific failure modes, interaction of failure modes, or possibly interaction of damage mechanisms. Additionally, tests with fewer components are generally less expensive than tests farther up the information hierarchy.

LFTs have the potential of providing the most information per shot and are the only way to observe the interaction of all the systems to multiple synergistic damage mechanisms. LFTs are either engineering shots or random shots. Engineering shots are selected to investigate specific system changes, such as vulnerability reduction measures (VRM), or to address other issues. Random shots are, as the name implies, selected to hit the target at a random location, azimuth, and elevation. Engineering shots could be thought of as designed tests; however, the small sample sizes associated with LFT and the absence of replicated shots do not permit good inferences on the issues. Additionally, the full-up LFT does not provide a controlled environment in which data can be collected at the appropriate stages or in quantities that allow high-confidence inferences. For example, an LFT provides no information on the characterization of behind-armor debris (BAD), because the data collection techniques are invasive to the test outcome. Also, since each of the LFTs will likely impact a different section of the target, many components are never affected by the shots and many others are affected by only a very few shots. Nevertheless, given that a model is hypothesized as simulating the actual LF event, it takes fewer shots to validate the model than it would to create the model. For validation of the simulation over many target-threat combinations, there is no substitute for full-up LFT data. Many submodels, such as BAD generation can be validated with other test data; however, only LF data provides all the damage mechanisms against all systems as well as their synergistic effects.

An additional consideration is the requirement that, for LFT, the system being replaced is tested "side-by-side" with the new system. Therefore, the cost to LFT the Paladin, for instance, should include the cost to LFT the M109A2/A3 on a shot-by-shot basis. Obviously, this escalates the total cost of LFT. Of course, if the system has an entirely new mission, then this is not a factor. Further discussions of live fire modeling can be found in Deitz, Saucier, and Baker (1996) and in Deitz and Saucier (1996).

3. CONNECTIVITY OF DAMAGE-TO-ENGINEERING CAPABILITY IN THE ACQUISITION PROCESS

The V/L process structure provides an approach that applies to areas other than V/L analyses. Recall, all events, through the determination of remaining capabilities, are engineering observables or measurables; that is, one could physically observe or measure these phenomena in the field. Consequently, the process structure, specifically, the use of fault trees to describe the functionality of subsystems and capabilities, permits analyses across the spectrum of Army concerns for a combat system based on the same set of required capabilities. This increases clarity about which capabilities are important and provides a tool for communication among the analysis community. Several such applications include: (1) comparison of analytical predictions with experimental results; (2) battle damage repair (BDR) analyses; (3) RAM analyses; (4) Operational Requirements Documents (ORDs); and (5) force-level war games.

3.1 LFT Assessment Process. An important application of the V/L process structure is in the comparison of analytical data with results of actual testing. The approach promulgated by the process structure provides an excellent means by which to evaluate both live fire experimental data and potential shot locations prior to actual firings. Analytical predictions allow the evaluator to select the most meaningful shots; thus shots which may provide minimal data can be eliminated, or shots which could result in catastrophic loss of the system can be postponed until the end of the shot series.

Most importantly, a combination of experiments and modeling can be employed to maximize the characterization of system capability while minimizing the cost of such characterization. A critical requirement for analytical methodologies to be used in this manner is that the methodologies parallel test events and have outputs which are measurable and/or observable. Validation of methodologies, the output of which can only be inferred indirectly from test events, is at best extremely difficult. The V/L process structure defines an appropriate framework for such methodologies.

Traditional combat utility metrics that infer battlefield effectiveness directly from damaged components suffer from two major difficulties. First, such metrics assume no variability in engineering capability from a given damage vector; test experience from both the Joint Live Fire (JLF) and the Army Live-Fire (ALF) test programs has shown this assumption to be false. Second, since these traditional measures constitute an average over all mission and scenario factors, they provide no means for assessing individual subsystem capability in specific contexts. The recent conflict in Southwest Asia pointed this out in dramatic fashion,

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with U.S. armor performing at levels far above the average expectation. Such assessments can only be done at Level 3. The use of fault trees allows one to get to Level 3 in the V/L process as well as providing the crucial interim step between Levels 2 and 4. Going directly from Level 2 to Level 4, that is, inferring combat utility directly from system damage as is done with the traditional Standard Damage Assessment List (SDAL), does not provide a measurable or observable output. Thus, one cannot relate the damage from the LFT to the LOF value provided by the SDAL or even to battlefield utility; there is no direct comparison between the two. The fault trees, in tandem with the V/L process, provide the means for this direct comparison; it is the inclusion of Level 3 which makes this possible.

3.2 <u>BDR</u>. Figure 4 depicts the analytical paradigm for the BDR methodology, laid out in terms of the V/L process structure. BDR, or any kind of repair, can be modeled using the V/L process structure approach in the following manner. Given an initial set of component damage at Level 2, a mapping can be performed (using the DSVM) to determine the remaining capabilities of the system at Level 3. This represents the capability of the system given no repair is performed. If one can establish repair priorities and required repair times, one can perform a sensitivity analysis to determine the usefulness of repairs by attempting to do whatever repairs are possible in the allotted time. This provides a second set of damaged components, one which is (possibly) a subset of the original set. Using this new damage component vector (Level 2), a mapping is performed again to determine the remaining capabilities of the system given the affected repairs. After a comparison is made between the original set of remaining capabilities and the new set resulting from repair, an assessment can be made of the usefulness of the repairs (i.e., what did it gain the system in terms of capabilities).

A series of repairs can be identified, and sensitivity analyses performed, to determine what capabilities the system gains as a result of varying amounts of repair time and parts stockage. These analyses can indicate what repairs are necessary in terms of system performance, what types of spare parts need to be stocked, and what the critical path is in terms of needed repair. It should be noted that when the repairs are attempted a system may remain at the same damage point as the one before repairs were affected (i.e., not enough time was allocated). Conversely, a system may be returned to fully functional if all the damaged components were repaired. In addition, the sensitivity analyses may indicate whether or not the system can continue a certain mission, given the capabilities required are available.

Another way to view the BDR methodology is to start at Level 4 and ask the question, what is the system's mission and what capabilities are needed to accomplish it? This returns the system to Level 3

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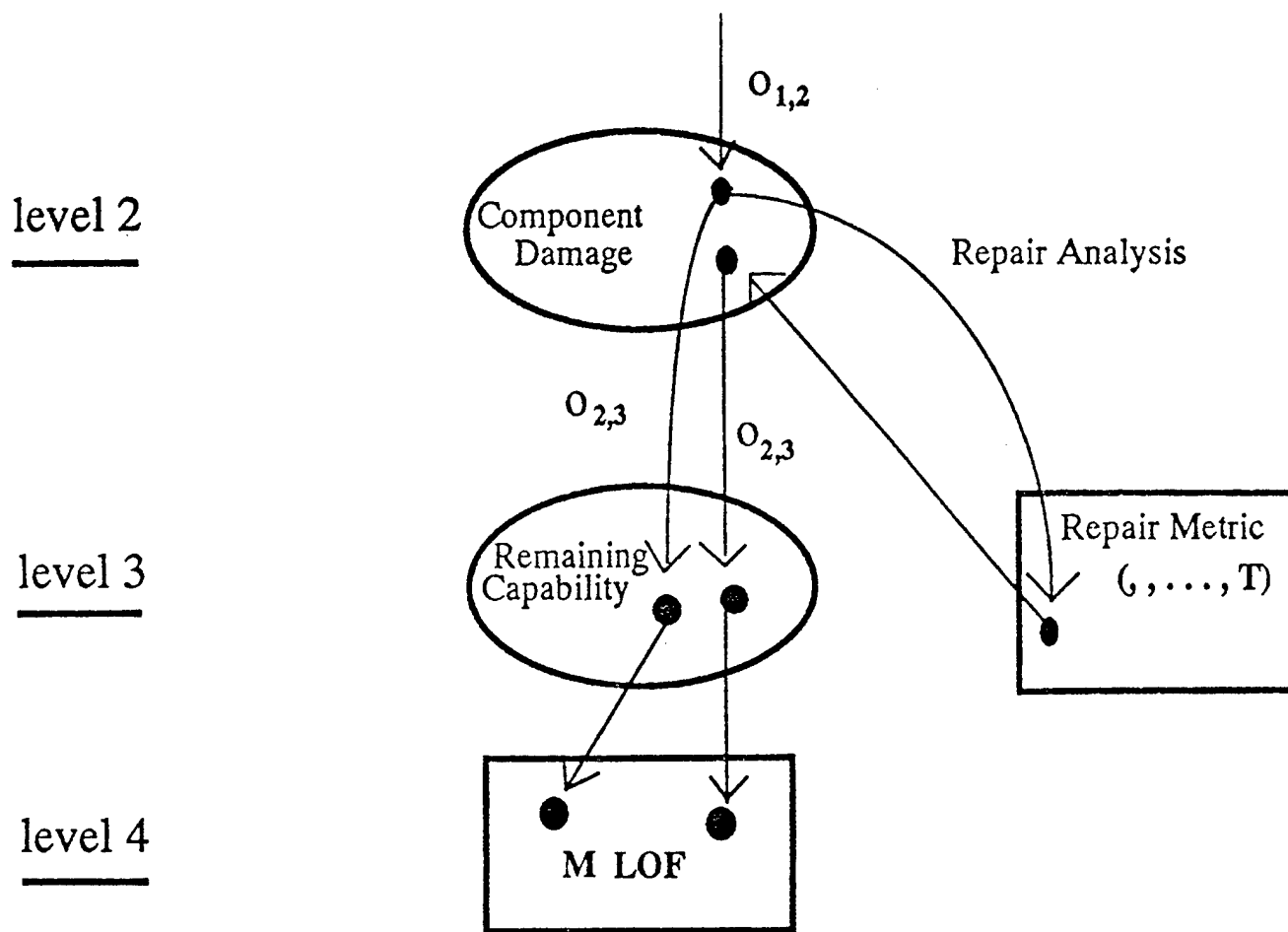
Figure 4. Proposed BDR methodology.

to determine whether or not the capabilities are available. If not, the path is traced back to Level 2 to determine what components are needed to permit the functioning of the capabilities required to accomplish the mission; this gives an indication of what components need to be repaired.

Currently, there is no uniform treatment of repair across the triservices or even across combat arms within the Army. The BDR methodology described here solves the problem and provides auditability and consistency of results. It also provides an approach whereby a standard accounting of consequences, in terms of performance and cost, of various levels of repair can be determined; this permits uniform comparisons across the mission areas.

3.3 <u>RAM Analysis</u>. Another area of application for the process structure is the extension of fault tree analysis to address the problem of RAM. An effort is underway to identify the commonalities between the vulnerability and reliability analysis techniques. The use of fault tree analysis would not only clarify the capabilities of concern for the combat system but provide the same starting point for both vulnerability and RAM analyses. Although the damage mechanisms may be different, the effect on the combat system's functionality should be the same for a given set of lost components. To investigate the feasibility of this proposition, the Ballistic Vulnerability/Lethality Division (BVLD) formed a working group with the AMSAA Reliability, Availability, and Maintainability Division (RAMD) to address problems such as familiarization with each other's analytical methods and determination of a single nomenclature for use in both V/L and RAM analyses.

The initial premise of this effort was that the methods for assessing the damage may take different approaches but should yield the same results. Both analyses are concerned with determining remaining combat system capability once a component becomes nonfunctional. That is, both must assess combat system damage. The V/L analyst determines the lethality of a weapon or the vulnerability of a combat system in terms of functional damage; the RAM analyst determines the reliability of the combat system by investigating functional failures. To do this, both analysts must develop an understanding of component interrelationships and relate these components to the system's required capabilities. While the V/L analyst is concerned with critical components (i.e, components required to allow mission performance), the RAM analyst is concerned with all components. For example, the commander's seat is noncritical in terms of mission performance for a V/L analysis and, therefore, is not considered during the analysis. However, a RAM analysis needs to assess the commander's seat in order to determine whether or not it meets its reliability criteria. The components of concern for the V/L analyst are a subset of those of concern to the RAM analyst. Once the capability levels are identified and the fault trees developed, each analyst could select those fault trees applying to his/her analysis.

The objective of the initial BVLD/RAMD investigation was to determine if the two methods yielded the same results and to investigate the differences and similarities in order to determine where the two processes could be combined. The initial effort established the functional loss of the M1A1 for a given set of killed components, selected from a recent vulnerability analysis. This set of killed components was used by both reliability and vulnerability analysts to assess which functions on the vehicle were affected. Each used his normal procedures. For the vulnerability analyst, the criticality analysis of the M1A1 was consulted. The reliability analyst made use of the RAMD Failure Criteria Document for the M1E1 tank

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and conversations with the M1A1 project manager. The RAMD failure criteria use block diagrams which group components by function (e.g., mobility, fire control, etc.). This allows the analyst to show the relationship between the function and the components that make up the function. A description is then developed for the block diagram, which contains narrative representations of the basic functions followed by failure modes of the hardware associated with the function. This description reports which components cause functional loss, functional degradation, or have no effect at all.

Once the individual analyses were completed, the results were compared. Although there appeared to be, in general, no disagreement in assessed functional loss, the different processes and nomenclature made it difficult to be certain. The reliability assessment provided more specific information on functional loss, but required more effort than the vulnerability approach. Generally, the comparisons were fairly straightforward, however, some difficulties did arise. For instance, some components contributed to more than one function and thus were described in more than one RAM narrative section, depending upon the function being described. Unless the RAM analyst knew this a priori, not all loss functions may be identified. A second, more common problem, dealt with matching functions selected by the analyst when developing their criteria. In some cases, it was unclear if the two analysts were describing the same functions.

A single set of combat system capabilities should be identified early in the developmental cycle for use in all system analyses, including VL, RAM, and logistics. Techniques employed have not been consistent across organizations, most likely due to a lack of realization by the various analysts/project managers of the inherent similarities, resulting in the development of different capability requirements for different applications. Developing the list of required capabilities early in the cycle would avoid the aforementioned comparison problems and provide the basis for all subsequent analyses of the combat system.

These examples indicate that the use of fault tree analysis could make the RAM process easier and faster. Additionally, if fault trees for a given combat system were developed jointly by ARL and AMSAA analysts, early in the analytical process, some of the differences in answers could be avoided, or more easily accounted. As a result, BVLD and RAMD agreed to a joint effort aimed at developing common standards and practices for the identification of required combat system capabilities, the components that contribute to each capability, and the interrelationship of these components to overall system functionality and impact when the component (or subassembly) is lost or partially lost. This effort is intended to

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develop a standard technique for use by all organizations. Development of this technique will enhance the Army's ability to provide detailed and consistent system capability requirements across the spectrum of analyses. In addition, savings can be identified in terms of both time and money by the reduction of duplication of effort. It is anticipated that this effort will be the starting point for all subsequent combat system analyses to include vulnerability, RAM, logistics, survivability, and effectiveness.

3.4 ORDs. An additional application of fault trees is the determination of capability criteria for ORDs. Per DODI 5000.2, an ORD is a formatted statement containing performance and related operational parameters for a proposed concept or system. The initial ORD describes each concept proposed at MS I to include terms of minimum acceptable requirements that define the system capabilities needed to satisfy the Mission Need Statement (MNS). The ORD is updated and expanded for MS II to include thresholds and objectives for more detailed and refined functional capabilities and characteristics. These updates are based on the results of the tradeoff studies and testing conducted during Phase I (Demonstration and Validation). The ORD is then used to develop the system's requirements for contract specification through each acquisition cycle.

One of the major objectives of the ORD is to define the required functional capabilities and requirements. These definitions are to include an objective which represents a measurable, beneficial increase in capability or operations and supports the minimum acceptable level specified in the document. Historically, though, these objectives have been defined in terms, usually probability of kill (Pk), which are both physically unmeasurable and vague in quantification. Because of these inherent problems, definition of the requirements in terms of the system's required capabilities (at Level 3 in the V/L process structure) would provide well-defined, measurable objectives. As an example, the application of the DSVM approach to the Advanced Field Artillery System (AFAS) will be discussed. This work was initially performed at the direction of the Program and Vulnerability Assessment Office of the Assistant Secretary of the Army for Research, Development, and Acquisition (SARDA). (It should be noted that this approach works just as well for lethality [i.e., missiles] as it does for vulnerability/survivability of combat systems. Thus, the use of the term "combat system" implies any system which can be described in terms of required capabilities.)

The AFAS is the future self-propelled howitzer, designed as the replacement for the M109A6 Paladin. The proposed ORD for AFAS was reviewed with selected functional requirements rewritten in terms of required capabilities. As neither the firepower nor the mobility requirements were described in terms of

physically measurable quantities, suggestions were made as to how these requirements could be rewritten. Firepower, for example, could be expressed in terms of lower and upper bounds of an acceptable level as shown in Table 1.

Table 1. Example Firepower Requirements

		Requirement
		Rate of Fire
Acceptable Bound	Upper	at least 12 rd/min for 5 min
	Lower	not less than 6 rd/min for 5 min

The same type of physical, or engineering, metric could be applied to the mobility requirement. For example, speed could be defined in terms of the required (and desired) level for different environments (i.e., at least 25 mph in European rolling hills or 40 mph in Southwest Asian desert).

The quantification of the requirement in terms of engineering metrics permits easier evaluation as to whether or not the requirement has been met. The benefits of this approach are numerous. First, the requirements are expressed in terms of capabilities which can be explicitly measured and which are separated into the different capability categories (i.e., mobility, firepower, and acquisition). It provides a means for the user to prioritize the capabilities most worth preserving as well as provides greater insight into the military utility of the system and the effectiveness of each of its subsystems. Most importantly, it provides greater clarity as the user and developer of the system discuss tradeoffs between what capability is wanted vs. what can be affordably built.

3.5 Force Level War Games. The modeling of system functionality with fault trees, as a part of the mapping from Level 2 to Level 3 in the V/L process structure also has consequences for force-level modeling. It permits a more accurate portrayal of the system's remaining capabilities as a result of nonfunctional components, either through combat damage or failure. As currently modeled, the system is either fully functional or fully nonfunctional. A more realistic approach would be to model the system as still functional but in a degraded operational mode. This would result in a system remaining in the engagement longer and possibly affecting the outcome of the game. In addition, information from Level 2, component damage, would provide detailed information on damaged parts, thus providing more

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accurate data on spare parts requirements and the need for BDR (as discussed in the previous section on BDR).

A current effort underway between the BVLD and the U.S. Army Training and Doctrine Command (TRADOC) Analysis Center at White Sands Missile Range (TRAC-WSMR) is investigating the inclusion of DSVM metrics in the CASTFOREM force-level model. Specifically, the BVLD and TRAC-WSMR are modifying the CASTFOREM model to accept the DSVM metrics as well as store the damaged component vectors available from the $O_{1,2}$ mapping. The inclusion of the DSVM metrics and component information in this model will allow RAM and BDR to be played directly in the models and their effects on the systems and battle outcome to be directly measured.

3.6 <u>Summary Connectivity of Damage-to-Engineering Performance in the Acquisition Process</u>. Both fault tree analysis and the general V/L process structure have applications in areas outside the realm of V/L, as evidenced by the discussions within this section. The process structure allows the V/L models to closely parallel LFT&E events, thus providing calibration points for these models. Further, the ability to clarify the operational requirements of a system by identifying its required functions provides a sound basis for communications between the user and the developer throughout the acquisition life cycle of the system. The same analytical approach can be applied to RAM and BDR analysis, which allows one to evaluate the major aspects of the acquisition cycle using the same process. Finally, the inclusion of the damage vector information and the DSVM metrics in force-level models, such as CASTFOREM, will allow the major aspects of the acquisition cycle to be played simultaneously. The overall improvement in communications and analyses, as provided by the V/L process structure, can only improve the Army's ability to provide timely, credible analyses.

4. THE ROLE OF LIVE-FIRE TESTING (LFT)

4.1 <u>Department of Defense Regulation 5000.2-R</u>.

DOD 5000.2-R requires test and evaluation programs to be structured to integrate all developmental, operational, and LFT&Es as well as modeling and simulation activities into an effective continuum throughout the acquisition cycle for applicable combat systems. In fact, DOD 5000.2-R requires test and evaluation planning to begin in Phase 0, Concept Exploration, of the acquisition cycle.

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Figure 5 indicates where in the first three phases of the acquisition cycle the most significant events regarding survivability occur as well as their linkage to program technical initiatives and to the maturation of system technical attributes.

Conventional ballistic vulnerability reduction concerns the response of the target vehicle to an interaction with a threat munition and is a major component of survivability. The success and effectiveness of the vulnerability reduction effort is obviously related to the choices of technical solutions to mission needs identified in the initial Materiel Need Statement, the maturation of these technologies, and their incorporation into system design during Engineering and Manufacturing Development. A comprehensive vulnerability reduction, analysis, and experimentation program, though, is required to ensure a successful transition from concept to production insofar as the selection, development, optimization, and integration of vulnerability reduction alternatives into the final system design. Systems engineering, for example, is a management process espoused in DOD 5000.2-R to translate operational needs into a configured system through a systematic integration of technical inputs from the entire development community. Risks are characterized through early testing and demonstrations of system elements. The ultimate objective of the systems engineering process is to ensure and verify that the system design meets the operational needs.

While DOD 5000.2-R requires an assessment of the survivability to all threats found in the various levels of conflict prior to Milestone II and, in a general sense, vulnerability testing relatively early in the acquisition cycle, the only specific vulnerability testing program identified is the LFT, which, if conducted, occurs immediately before full-scale production.

Congress has mandated in Title 10, United States Code, Section 2366, that ACAT I and II programs for covered systems (vehicles, weapon platforms, or conventional weapon systems designed to provide some degree of protection to the user in combat) must include provisions for vulnerability LFT. Such testing is intended to demonstrate and, in conjunction with modeling, determine the vulnerability characteristics of the candidate system to the spectrum of threats likely to be encountered in combat. The statute provides a waiver if it can be demonstrated that LFT would be prohibitively expensive or impractical and it can be shown that the survivability of the system can be evaluated in other ways. Such a waiver must be made prior to the beginning of the Engineering and Manufacturing Development phase.

Since LFT is the only vulnerability testing specifically identified in DOD 5000.2-R, it may be

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LFT & E TECHNICAL PROCESS

ACQUISITION PHASE	MS 0	PHASE 0 CONCEPT EXPLORATION	MS I	PHASE I PROGRAM DEFINITION & RISK REDUCTION	MS II	PHASE II ENGINEERING & MANUFACTURING DEVELOPMENT	MS III

EVENTS

MNS Proposed

Threat Generally Defined

ORD Prepared

Initial Threat Assessment

PMO Formed

Initial TEMP

LFT

PROGRAM TECHNICAL INITIATIVES

- Explore alternative concepts
- Identify most promising concept(s)
- Determine surv. characteristics
- Identify crit. tech. shortfalls

- Define crit. parameters & cap. of concept(s)
- Demo. crit. tech. in design
- Technology, etc. risk reduction

- Translate best concept(s) into system design
- Demo. best system capabilities
- Validate manufacturing and production process

VULNERABILITY MODELING (ANALYSIS)

- Low-res analysis of concepts

- Low - medium resolution analysis of concept baseline
- Lo-res analysis of alternatives

- High-res analysis of system configuration
- Subjective VR analysis

EXPERIMENTAL SUPPORT

- Characterize emerging technology

Component testing

Limited BH&T

Further component testing

- Subsystem testing
  • Est. failure mode, symptoms
  • Char. specific VR concepts
  • Est. VR perf. limits
  • BH&T or STA

- System tests
  • LFT
  • DT/OT piggyback

METHODOLOGY, CODE DEVELOPMENT / IMPROVEMENTS

- Incorporate emerging technology

- Refine algorithms to model new technologies

- Specific system characterization
- V&V emphasis

Figure 5. Acquisition process.

appealing to defer experiments, testing, and analysis until the time LFT is to be conducted. However, LFT should, in actuality, be the culmination of a much more comprehensive and long-term vulnerability reduction, analysis, and experimentation program that includes not only the formal LFT but all vulnerability analyses, experiments, and testing conducted from concept exploration through low rate production. Relying on only LFT to address system vulnerability not only places undue risk in the program but practically ensures the system will exhibit less than optimum vulnerability characteristics. A well-formulated vulnerability reduction, analysis, and experimentation program initiated early and structured in a building-block manner will ensure more robust system survivability and can reduce or even eliminate the need for expensive full-up LFT just prior to full-rate production.

4.2 Vulnerability Reduction, Analysis, and Experimentation Program Structure

The vulnerability reduction, analysis, and experimentation program must address system survivability from three points of view. First, it must ensure requirements for vulnerability reduction evolving from the initial Materiel Need Statement are reasonable, achievable, and practicable. The whole battlefield threat likely to be encountered must be addressed. System survivability must not depend on technologies that cannot be reasonably expected to mature during the acquisition process or which have an unacceptable risk of doing so. On the other hand, requirements should be aggressive enough to take advantage of, or even challenge, existing applicable technologies. Incorporation of vulnerability reduction features into system design must not unduly burden other design parameters. Even more importantly, they must not sacrifice fightability.

Second, the vulnerability reduction, analysis, and experimentation program must be formulated to help the materiel developer ensure that design requirements are being met as the acquisition cycle progresses. But, even beyond requirements, the program must stimulate measures that can and should be taken to optimize vulnerability reduction against threats or conditions beyond the actual design requirements. The focus here is on applying good engineering principles to reduce vulnerability and ensure the design is relatively insensitive to at least minor variations in threat characteristics with minimal additional design cost.

Third, the vulnerability reduction, analysis, and experimentation program should be structured to reduce program risk by ensuring successful completion of LFT. These tests are conducted on production hardware, which means they are conducted very late in the development cycle. Clearly, problems

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identified during LFT will be costly to remedy and will most certainly at least delay the MS III full-rate production decision. In an aggressive vulnerability reduction, analysis, and experimentation program, problem areas will be identified and addressed long before the design is finalized and in time to effect appropriate corrective measures.

The vulnerability reduction, analysis, and experimentation program should be structured to progress in a manner that allows all efforts to take advantage of and build on previous efforts. Procedurally, a combination of analytical modeling, experiments, and analysis methodology development is necessary. Modeling progresses from low-resolution analyses of design concepts early in the acquisition cycle to high-resolution modeling to support LFT near production. Experiments are conducted early to characterize the ballistic performance of new materials or design concepts. As the system matures, the experiments on design concept components and even on prototype components become more extensive in an attempt to characterize the vulnerability of what will eventually be the actual design. Eventually, laboratory experiments give way to field testing culminating with the LFT just before full-rate production. Damage mechanisms and component/subsystem failure modes that cannot be adequately modeled with extant methodologies must be addressed in methodology development efforts.

Neither the analyses nor the experiments and testing are conducted in a vacuum. Experimental and test results are used to formulate inputs to the modeling codes. Conversely, analytical results provide valuable guidance to experimental design. Figure 5 shows the types of experimental and analytical activities required throughout the acquisition process and suggests the way these activities are linked to provide a coordinated comprehensive vulnerability reduction, analysis, and experimentation program. The following comments discuss these activities and indicate the purpose and granularity of each activity as the design and development proceeds.

In the early stages of the acquisition process, the primary focus with regard to vulnerability reduction, analysis, and experimentation is on low-resolution modeling. Because only concepts are being considered at this stage, there is not enough system design detail to permit high-resolution modeling. In fact, what is needed at this stage are analyses to define the potential of competing concepts to reduce vulnerability and to define the limits or bounds of vulnerability reduction that may be achieved if a given concept is selected for system development. Ancillary analyses may be performed to assist in the preparation of the ORD. It is essential that the ORD contain vulnerability reduction requirements that are appropriate given the projected threat environment and usage of the objective system but at the same time are achievable

with available technology without putting an undue burden on other design parameters. Again, since design details of competing concepts are usually sparse at this point, the analyses attempt to capture the potential (or lack of potential) of major vulnerability reduction technologies known to be seriously considered. The aim is not to quantify, in absolute terms, the vulnerability of any system but to ensure the proper rank ordering of competing concepts.

Because of schedule availability, this is an optimum time to conduct a high-resolution analysis of the system being replaced, if that is the case, or of the system(s) being supplemented by the new system. This will establish a baseline quantification of vulnerability that will be used later in the acquisition cycle to gauge the improvement achieved in the new system. (Care must be taken, though, to resist comparing low-resolution model analyses of concepts with the high-resolution analysis of existing system(s) because the basis of comparison, namely relative target description detail, will be faulty.)

Experiments should (or in some cases must) be conducted to get a handle on the vulnerability reduction characteristics of emerging technologies. Examples of such experimental efforts include characterizing the ballistic performance of composite or other new materials, determining the impact sensitivity of stowed munition energetic components, and identifying likely failure modes for sensitive electronic components. It is not usually necessary that these experimental investigations be extensive since there is no assurance that investigated technologies will be pursued in development (at least at the detail level, composite armor might be ultimately used, but the specific armor may not be known at this point, for example). However, it is often necessary to conduct adequate experimentation to generate rules of thumb that will bound ballistic performance, provide insights into potential failure modes, and guide technology integration. For example, it would probably not be necessary to generate new penetration equations for all new types of materials but it would be necessary to conduct enough experiments to calibrate existing equations for similar materials to be able to predict approximate penetration performance.

There may be a need to begin to improve or even extend analysis methodologies at this point if it appears that extant methodologies will be deficient later in the program. Whether this is desirable or even possible will depend on the likelihood of various technologies being pursued later in system development. This underscores the importance of a comprehensive and continuing experimental program beginning at the earliest stages of the program.

During the latter part of Phase 0, Concept Exploration, and during Phase 1, Program Definition and

Risk Reduction, both analyses and experiments become much more system specific than they were earlier. But, there may still be many gaps in system design details and tradeoffs will continue to be conducted to define the system configuration. Low-resolution analyses, and even high-resolution analyses of existing prototypes in many cases, should begin to focus on specific questions and issues related to system design. The ORD contains specific system requirements that can also be addressed. One important task is to recast ORD requirements that are typically stated in terms of taxonomy space 4 metrics (loss of combat capability) into a suite of system performance metrics (space 3). These metrics, which can be tested, are valuable for characterizing the vulnerability of the system in terms that can, with follow-on effectiveness modeling, truly address survivability in several different mission scenarios.

Later as prototypes mature, it is possible to critique emerging designs and apply engineering design principles that foster vulnerability reduction. Examples include using redundancy for hydraulic, fuel, and electrical circuits; locating critical components to use protection afforded by heavy structures; and determining optimum armor coverage.

In the same manner, experiments can be conducted to characterize component vulnerability, including identification of significant damage mechanisms and failure modes. Experimental efforts will focus on space 2 metrics and space 1–2 mapping, although consideration of space 3 metrics and consequent space 2–3 mapping should also begin. For armor systems, BAD characterizations are usually necessary. The scope and complexity of these experiments will vary depending on hardware availability and design maturity. It is desirable for these experiments to be as thorough as possible at this point, because the data will be required for subsequent analyses and will also be useful for detailed design in the Engineering and Manufacturing Development phase. It may be desirable to conduct limited subsystem level tests at this time. Examples would be ballistic hull/turret tests of armor vehicle designs to determine BAD distributions and quantify the potential of mitigating schemes.

Vulnerability analysis model development should now focus on continuing development of algorithms to account for new damage mechanisms and failure modes or to model new system technologies. The definition of degraded states begun previously should be refined to reflect maturity in both system design and operational deployment concepts.

As the definition of the system matures, it is both possible and necessary to conduct more definitive analyses and more comprehensive experiments and tests. Beginning early in Phase 2, Engineering and

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Manufacturing Development, high-resolution modeling is used to help system designers choose among vulnerability reduction alternatives. These analyses define the potential payoff of competing alternatives as well as some of their costs, particularly space and weight. Once specific design concepts have been chosen, further analyses can be used to generate data to help perfect the design. Both high-resolution modeling and the continued application of vulnerability reduction design principles are necessary to accomplish this objective. Even though system design is now focused on meeting specific design requirements, including those for vulnerability reduction, high-resolution modeling affords an excellent opportunity to analyze the vulnerability of the system to the spectrum of battlefield threats. It will usually become apparent that some threats can be easily defeated or tolerated if the design requirements are met. Others will be shown to be overmatches, which may be impractical or impossible to totally defeat. But, it may be possible to mitigate the effects of these threats under at least some combat conditions through the judicious application of vulnerability reduction engineering principles. Often, significant gains in protection can be achieved at little additional cost. It is not the purpose of modeling to design the system but to generate data through which the best design can evolve.

As with analyses, this is the opportune time to conduct experiments to further develop component failure modes and gain better insights into the threat damage mechanisms to which the design is particularly susceptible. Hopefully, the experiments conducted to this point will have produced the basis for continued experiments focusing more on subsystem and system attributes. As the system design matures, it is possible and affordable to conduct a much more comprehensive set of experiments to investigate and quantify these phenomena. Subsystem level, and later, system level experiments and field tests should be conducted to identify and investigate synergisms that cannot be thoroughly addressed at the component level. While many of these synergisms can be anticipated quite early, even in preceding phases, experiments and tests at this point can be conducted in a manner that will foster the identification of unanticipated synergisms. This is accomplished by including as many components in the test assembly as possible and by instrumenting for data that otherwise might not be deemed necessary. Subsystem tests are also necessary to fully establish selected vulnerability reduction performance limits. For example, a full suite of production armor mounted on a complete chassis may behave far differently than subscale laboratory coupons in a laboratory fixture. Development and operational tests (DT and OT) should be exploited when possible to both add to the test data base and to reduce the amount of full-up vulnerability LFTs. In this way, costs can be reduced through "piggy backing" onto the DT or OT rather than conducting dedicated vulnerability tests. For example, it is common to conduct DT on armor vehicles to ensure the armor installation and protection meet design requirements. This series could easily be

expanded to fire overmatching threat munitions to determine the upper limits of protection and include at least selected operational subsystems to determine their response.

The "ultimate" vulnerability test series is the LFT mandated for most combat systems. These firings are to be conducted on production quality hardware with actual threat munitions, or at least with approved surrogates when actual munitions are not available or are prohibitively expensive. As valuable and revealing as these full-up tests are, they are no substitute for coupon, component, and subsystem experiments conducted throughout the acquisition process. Full-up tests simply cannot produce the type and quantity of data needed to develop a detailed understanding of the underlying phenomena. This further emphasizes the need for a comprehensive vulnerability reduction, analysis, and experimentation program throughout the acquisition cycle.

Both modeling and component/subsystem level experiments support LFT. Modeling is used to help select shot lines and also (particularly high-resolution modeling) to predict test outcomes (preshot predictions). The experiments leading up to LFT provide input data for modeling (component kill probabilities, failure modes, limits of redundancies, etc.) and also reduce the likelihood of unpleasant surprises during the full-up LFT.

Just because a system has undergone LFT, is in production, and has been fielded, survivability cannot be neglected. Seldom will a system be fielded and retired without requiring design changes to address design deficiencies identified after production or to reflect changes in operational use or threat escalation. Advances in materials, design, and manufacturing technology also lead to design changes to reduce costs, improve performance, or add capabilities to the system.

Design changes for any of these reasons can affect system survivability. In fact, the LF legislation requires LFT for product improvements if the vulnerability of the system is potentially affected. The roles of analysis and experimentation are essentially the same as they are during system design except that usually it is possible to conduct more high-resolution modeling since the baseline system is well defined and, hopefully, well characterized. This allows the effect of specific design proposals to be thoroughly evaluated.

5. COST-BENEFIT OF FULL-UP LFT

The purpose of this chapter is to investigate various methodologies which would quantify the costs, risks, and benefits associated with full-up LFT and with various alternative testing strategies. Such a methodology should serve as a formal procedure for the request of a waiver from full-up LFT of a system. Four methodologies have been proposed, three by the Army (sections 5.1 and 5.2 provided by the ARL/Survivability/Lethality Analysis Directorate (SLAD)/BVLD, section 5.5 provided by University of Wisconsin by DOD contract) and one (section 5.4) by the U.S. Air Force (USAF). As might be expected, they all incorporate considerable subjectivity, and they vary considerably in the total effort needed for implementation. There are tradeoffs between simplicity, thoroughness, and perceived accuracy.

In the succeeding subsections, we will present the proposed methodologies, emphasizing areas of subjectivity and listing the advantages and shortcomings of each. There are valid arguments in favor of each proposal. Perhaps the final cost/risk/benefit methodology will evolve into some hybrid of the proposed methodologies.

5.1 <u>Decision Tree Methodology</u>. An example of this straightforward approach incorporates a series of 13 sample questions (see Table 2) pertaining to the costs and benefits of full-up LFT of a system. It represents an expert system of sorts in that the answers to the various questions will lead the user on a path that will eventually provide a decision concerning whether or not to apply for a waiver from full-up LFT, while simultaneously suggesting alternative testing strategies.

The initial five questions listed in Table 2 pertain to cost. We felt that the total production cost (determined by questions 1 and 2) was an important factor in the decision of whether or not to conduct full-up LFT, since one would be less inclined to perform such tests on an expensive system. The question as to what is meant by "expensive" requires an answer that is, of course, subjective. Indeed, subjectivity is present in most of the decision rules; and we will discuss this in greater detail later in this section. Question 3 checks on the availability of facilities for full-up LFT, and questions 4 and 5 pertain to the cost of performing such tests.

Table 2. Sample Questions Concerning Costs/Benefits of Full-Up LFT

Costs
1. What is the average cost of a system?
2. How many systems are to be produced?
3. What is the cost of facilities for full-up testing?
4. What is the cost of conducting a noncatastrophic, full-up LFT?
5. What is the probability of catastrophic kill given a full-up LFT?

Benefits
6. How important is system vulnerability to system survivability?
7. What percentage of the developmental cost is programmed for vulnerability reduction measures (for example, compartmentalized ammunition)?
8. How significant are the synergistic effects of damage mechanisms on multiple subsystems?
9. What percentage of the components have been previously tested or subjected to ballistic threats in combat?
10. What percentage of the subsystems have been previously tested or subjected to ballistic threats in combat?
11. Have other tests or analyses been conducted which enable conclusions to be drawn concerning overall system vulnerability?
12. What percentage of the untested components are projected for testing?
13. What percentage of the untested subsystems are projected for testing?

The remaining eight questions attempt to quantify the benefit of performing full-up LFT. Question 6 checks to see if the system is likely to be hit. If not, then perhaps the concern over the Pk/h is diminished. Question 7 checks on vulnerability reduction measures. The response to this question should be consistent with the response to the previous question. That is, if the system is not likely to be hit, then little money should have been programmed for vulnerability reduction. Question 8 covers synergistic effects of damage mechanisms on subsystems. If these might be significant, then there should be an inclination towards full-up LFT. Question 11 inquires about other testing and analyses (for example, nondestructive testing and computer simulations). Questions 9, 10, 12, and 13 examine previous and projected testing on components and subsystems. Obviously, if knowledge about the system exists from other testing and analyses, the need for full-up LFT is diminished.

A proposed decision tree is shown in Figure 6. Notice that we are inclined to test the "inexpensive" systems and grant a waiver for the "expensive" systems. In the middle, where many systems fall, we ask additional questions. A magnification of the boxed area in Figure 6 is shown in Figure 7.
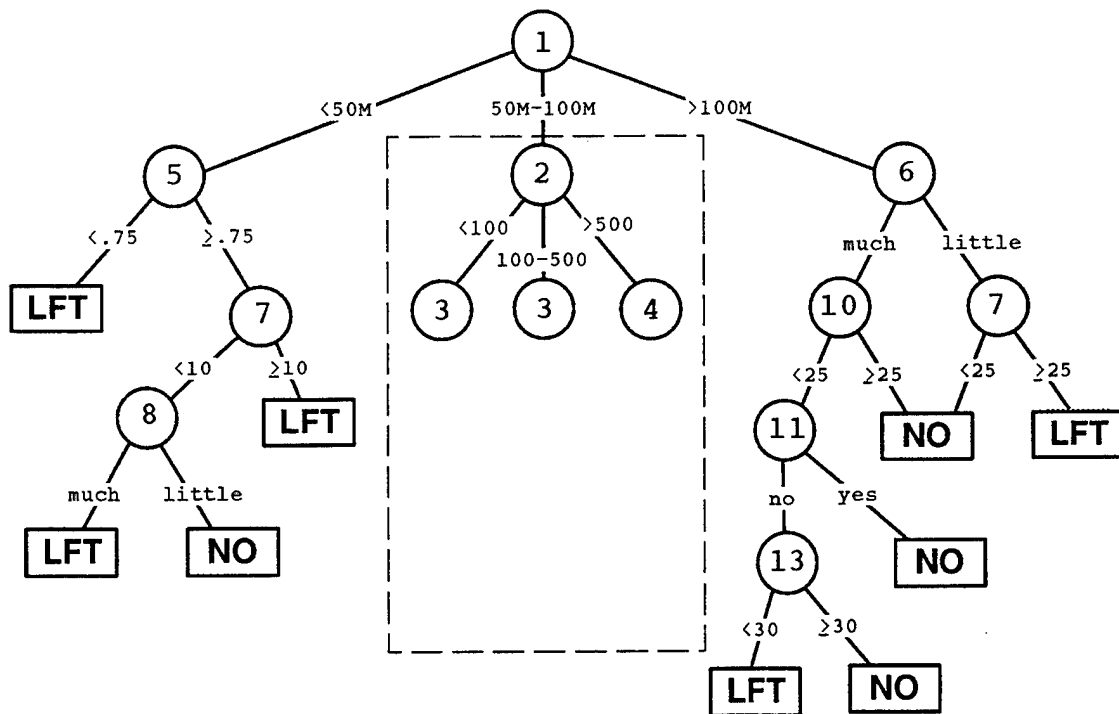
Figure 6. Sample decision tree.
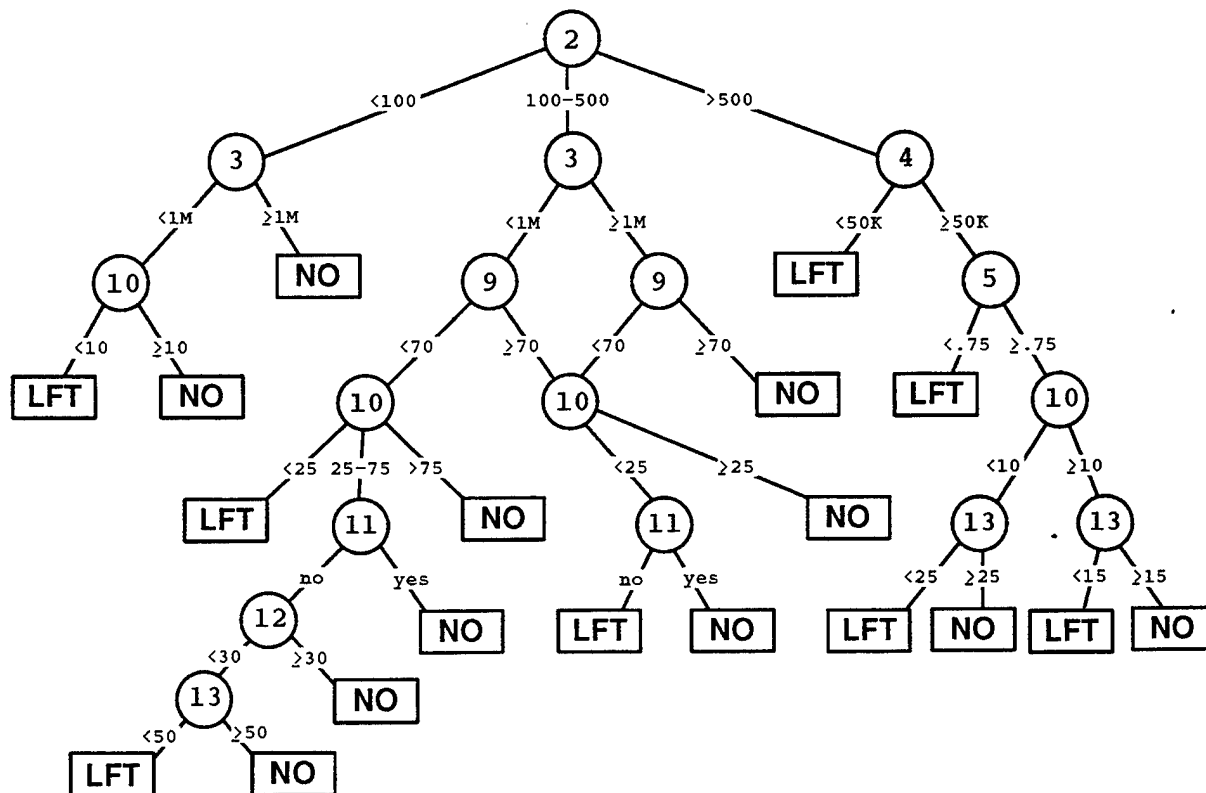
Figure 7. Magnification of the middle of the sample decision tree.

In working with the 13 questions, we have attempted to establish reasonable decision rules. For example, question 1 relates to the average production cost of a system. If this value is greater than $100M, we are inclined to waive the full-up LFT requirement; whereas, if this value is less than $50M, we tend to perform the test. However, note that the decision concerning full-up LFT is not based solely on the answer to this question. Cost values between $50M and $100M require additional consideration and some systems >$100M are live-fired because of other considerations. These threshold values were derived by examining the 1989 Military Cost Handbook published by Data Search Associates of Fountain Valley, CA. Data from this handbook are shown in Figures 11, 12, 13, and 14. In these figures, the term "average cost" represents the costs for the most recent (as of FY89) specific quantity procurement of an item excluding spares. Notice that support vehicles and tracked combat vehicles would all fall into the category of "less than $50M." This does not mean that they would all be subjected to full-up LFT, but it does indicate a likelihood of that decision. Many of the aircraft fall into the same category, with two (V22 Osprey and C17 CX) being "greater than $100M." Another half dozen require more detailed study. Over one-half of the ships fall into the "greater than $100M" category. Based on these data, we believe the decision rules, incorporating thresholds of $50M and $100M, are reasonable. If more accurate or recent data were provided, the rules should be reevaluated.

Of course, the decision rules are the most subjective feature of this methodology. They should generate much thought and may require periodic adjustments. In addition, there could be changes to the list of questions, perhaps rephrasing them in order to replace qualitative decision rules with quantitative ones. However, if this methodology were accepted (after any desired modifications), it would offer the following advantages:

- It is appropriate for all new systems without modifications.

- It can be implemented at MS II of the developmental process.

- The questions are straightforward with a minimum of subjectivity.

- Questions 9–13 can suggest a mix of testing on components and subsystems necessary to justify a waiver from full-up LFT.

- It provides an easy-to-understand procedure for submission of a waiver from full-up LFT.
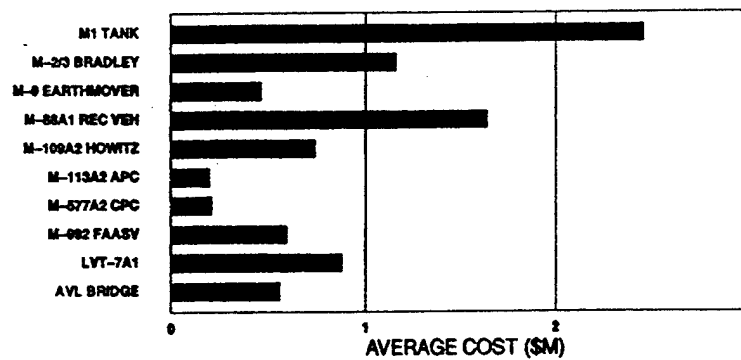
Figure 8. Average costs of tracked combat vehicles.
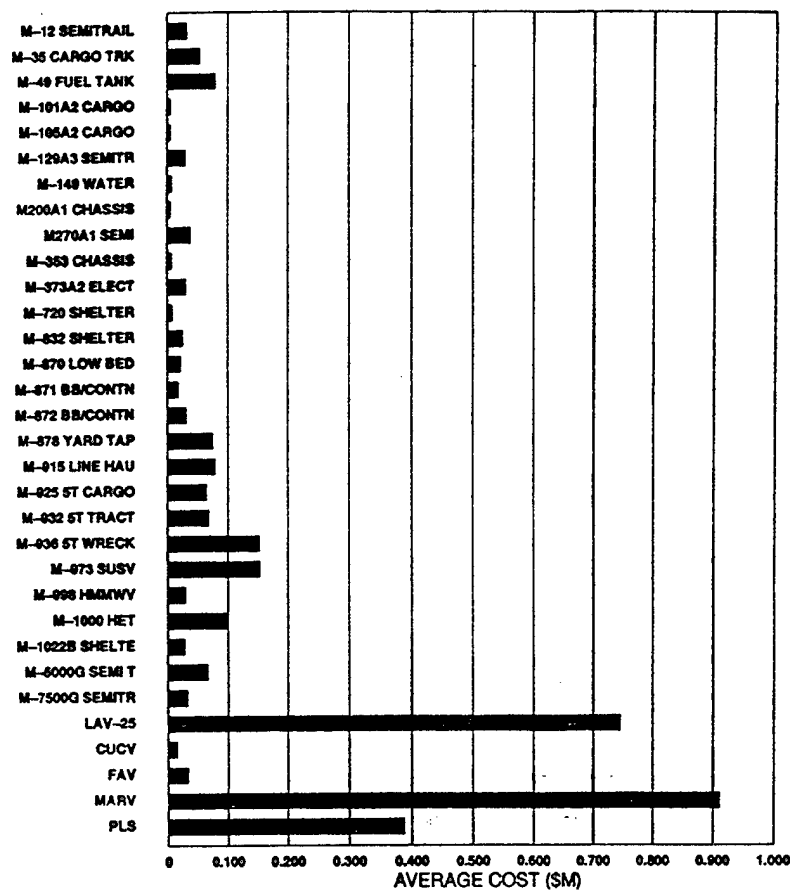
Figure 9. Average costs of support vehicles.

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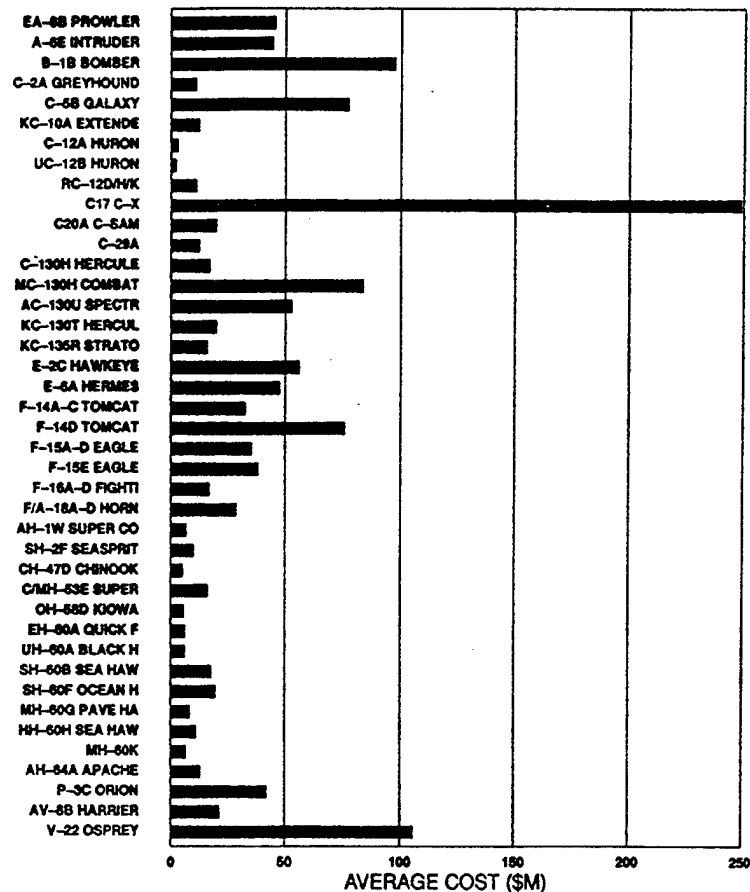
Figure 10. Average costs of aircraft.
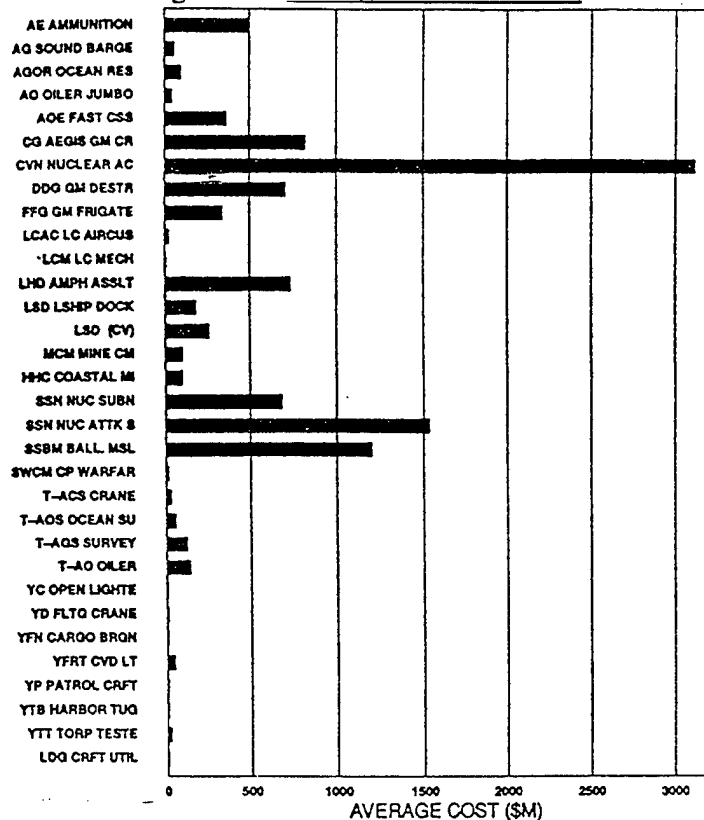
Figure 11. Average costs of ships.

This final advantage means that a Project Manager who wanted to request a waiver from full-up LFT would submit the following:

(1) A formal request for waiver.

(2) The trail through the decision process.

(3) The justification for decisions at each node of the decision tree.

(4) The threat document to substantiate such decisions.

(5) Any additional backup material deemed pertinent.

We emphasize that what we have presented is an example of the decision tree methodology. The actual set of questions might be modified, and the rules at each decision node could be altered. We encourage knowledgeable input in both cases. However, as a methodology, the decision tree remains a feasible procedure for incorporating the costs and benefits of conducting full-up LFT of a system in order to determine whether or not a waiver of such testing is justified. Its simplicity is appealing, but some may feel it lacking in rigor. A reasonable alternative is to use this methodology as a prefilter to examine systems that are either very expensive or very inexpensive. For those systems falling between these two extremes, a different more thorough methodology, such as those outlined in the succeeding sections, might be applied.

5.2 Knowledge-Based Methodology. The knowledge-based methodology is based upon the following principles:

(1) The goal of analysis is to provide information for decision makers. For example, see Operational Research in Practice: Report of a NATO Conference (Davis and Verhulst 1958). The author is indebted to the late Art Stein for this reference.

(2) The reason for testing is to provide data that is needed to improve analyses.

(3) There are many data-gathering techniques, each offering benefits in quality of data and carrying its own price. It is necessary to assemble a data-gathering plan that uses all appropriate techniques to obtain data of sufficient quality at a cost that is low relative to other plans.

To implement this methodology, it is necessary to show that:

- Quality of data can be quantified and related to testing.

- Decision making can be related to quality of vulnerability information.

- Expected costs can be estimated.

To quantify the quality of data, a number of techniques appear to be useful. (They are discussed in section 5.2.1.2.) In this section, we have emphasized one in which data are represented by intervals in which the data provider feels the true value lies. These intervals are amenable to quantitative interpretation in terms of accuracy and confidence.

To relate decision making to vulnerability information, the methodology concentrates on the required vulnerability information set (RVIS) which will be used by decision makers. Since this information is normally supplied through models, the relationship between data quality and model output is directly applicable to meeting decision needs.

The appropriate cost measure is an **expected cost** that reflects the probability of large costs accruing from unintended outcomes of tests. The use of expected costs is common in other fields.

A hypothetical example ("The Ballistic Bicycle"), which demonstrates several features of the knowledge-based methodology, is presented in section 5.2.3. In this example, three methods of quantifying data quality are used. In each case, the quality is propagated into the RVIS. A number of test plans are then proposed that involve different mixes of component, subsystem, and full-up munition tests; each of the test plans is refined to meet the RVIS quality requirements. Given they meet the quality requirement, through analysis of expected costs, the preferred plan becomes obvious.

A second hypothetical example (the F-16) is based upon an actual analysis performed on the aircraft at about MS II. Although differing from the Ballistic Bicycle in type of threat analyzed and vulnerability analysis technique used, the F-16 example employs a similar data quality evaluation technique.

It is important to note that the knowledge-based methodology does not completely eliminate subjectivity. The fact that this analysis must be made early in the development cycle of a system precludes the total elimination of subjectivity. However, it is clear that this methodology:

- Identifies the remaining subjectivities.

- Supports bounding those subjectivities and assessing their potential impact.

- Directly relates the subjective elements to possible testing.

The knowledge-based methodology offers several ancillary benefits.

- It requires that a global, coordinated data-gathering plan be assembled and analyzed early in the development cycle.

- It requires that confidence and accuracy in both data and analytical results be evaluated.

- It takes advantage of and augments analyses that are already an intrinsic part of every system development.

5.2.1 Benefits and Expected Cost of Data-Gathering. Every benefit/cost methodology obviously requires definitions and quantification schemes for the benefit being sought and the cost of the various alternatives for achieving that benefit. This section develops quantification schemes for the benefits and the expected cost of a data-gathering plan including testing. First, the following concepts must be defined.

5.2.1.1 Data-Gathering Plans. In this section, a test plan or, more generally, a data-gathering plan, refers to all of the testing and other information-gathering activities throughout the acquisition cycle of an equipment item. A list of potential sources of information includes:

- Prior Data.

- Analysis.

- Component-Level Tests.

- Subscale Testing.

- (Full-Scale) Subsystem Tests.

- Nondestructive Tests.

- Full System Tests, Without Fuel/Ammo.[*]

- Full System Tests.[*]

The strategy is to optimize the combination of these data-gathering methods to be applied to any given system.

It must be noted that the concept of a total data-gathering plan is applicable at any point in the acquisition cycle. In fact, as shown in a preceding section, the initial TEMP is a requirement at MS I. Subsequent to MS I, critical design parameters and critical technologies are defined and selected for incorporation into the concept item. Often, this process involves testing, which bears upon the analysis of the vulnerability of the emerging system and which reveals critical data voids. Thus, the ability to foresee the need for specific vulnerability information improves throughout the development cycle. In particular, at MS II, it is generally possible to formulate a data-gathering plan that takes into account all data accumulated to date and anticipates the kinds and amounts of data-gathering that will be required. This fits well in the sequence of analyses contained in the acquisition cycle (see Figure 5).

Note that it is not necessary to have a highly detailed model of a developmental item in order to anticipate the kinds of tests that will be required to meet decision data needs. In fact, it is very appropriate, at MS II, to use coarse and/or surrogate models to plan for tests that will produce data to be used in highly detailed analyses at MS III. Much of the disagreement that has arisen within the community stems from confusion regarding this point.

5.2.1.2 RVIS. Tying the "benefit" portion of the methodology to the quality of the vulnerability data that will be used in decisions raises three essential questions:

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[*] Includes operational tests/development tests (OT/DT).

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(1) What are the vulnerability data?   (Enumeration)

(2) How is its "quality" measured?   (Evaluation)

(3) What "quality" is required?   (Requirement)

In fact, it is the answering of these three questions that constitutes most of the difficulty in the development and implementation of this methodology. Much of the remainder of this section describes and gives an example of a few methods of enumeration, evaluation, and requirement. For this subsection, it is enough to describe the underlying concepts.

We refer to that set of information that satisfies the requirement for vulnerability information of sufficient quality as the RVIS.

Enumeration

On the surface, it might seem that the potential amount of vulnerability data is infinite. Indeed, there are an infinite number of possible combinations of fragment masses and velocities, blast overpressure-vs.-time curves, and other target-threat combinations. More subtle are the hidden vulnerabilities, sometimes referred to as the "unknown unknowns": single wires and unforeseen leakage flow paths and interconnected subsystems that can react synergistically to produce a much greater response to a threat than expected. These clearly cannot be enumerated.

However, if looked at from the perspective of the decision maker, there is a finite package of vulnerability information that will be used in studies and analyses that lead to a decision. As depicted in Figure 12, that information is combined with other information in the decision process. Often, intermediate steps are involved: for example, it is common for the vulnerability information to be combined with other aspects of survivability and scenario factors in simulations and war games. In such cases, enumeration of the RVIS is rather straightforward: it is that vulnerability data specified in the input lists of the simulations and war games being used. In other cases, a listing of the required vulnerability information may not be so rigorous. However, under any circumstance, it is clear that the amount of vulnerability information that will be used in decision-making processes is limited. Thus, concentration upon satisfying the needs of decision makers makes it irrelevant to ask questions about the existence of

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Future Scenarios

Cost Estimates

Political Factors

Force Mixes

Projected Uses

Susceptibility

Vulnerability

ACQUISITION DECISIONS

COMBAT SUCCESS

Mission Accomp.

Reduced Attrition

Casualty Reduction

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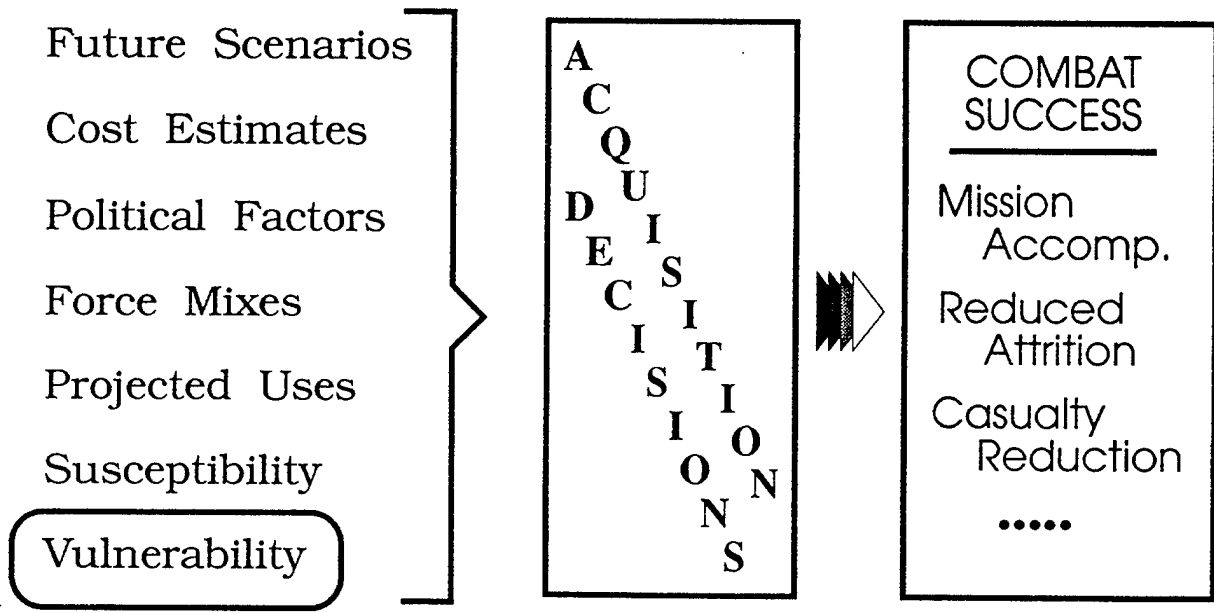
Figure 12. Roles of analysis in the acquisition cycle.

unknown, indeterminable vulnerabilities: if decisions will be made without their inclusion, it is consistent to neglect them in this methodology.

Vulnerability data requires significant processing before they are useful for decision making: a single test result has very little value to a combat model. Rather, if combat model results are used in a decision, the vulnerability data will have to be in a form such as single shot kill probabilities, vulnerable areas, blast contours, or lethal areas for the attacking munition. These data must come from vulnerability analysts. This observation has two important ramifications:

(1) The source of quantified lists of RVIS is the supplying vulnerability analysts.

(2) Enumeration of the elements of the RVIS is a matter of identifying the data which the decision makers require.

Evaluation

The definition and quantification of quality as applied to the RVIS constitutes the major research in this project. Although the work in this area is still ongoing, a few basic guidelines can be stated:

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(1) Quality must be related and relatable to successful decision making. This affirms the heuristic notion that RVIS quality is somehow related to the accuracy and importance of the data.

(2) The definition and the quantification of quality must be adaptable to all kinds of military systems and threats.

(3) The definition and the quantification of quality must be flexible enough to take advantage of the data and analyses available at MS II. In view of the markedly different development cycles pertinent to land, sea, and air platforms, this is a most demanding guideline.

Generically, the approach to quantifying quality is suggested by Figure 13. The concept is as follows: Instead of inputting specific numbers (point estimates) for data required by the vulnerability models, the analyst inputs numbers with associated indicators of their quality. The model propagates the quality along with each datum. The output, along with the required vulnerability information, is an expression of the quality of the information. For example, the quality of the data to be used by the analyst may be expressed as an uncertainty in the data values. The outputs of the vulnerability models, which constitute the information that supports acquisition decisions, will have an associated uncertainty that reflects the quality of that information. To be justifiable, testing should lead to a lower uncertainty (higher quality) in the output information.

In practice, the currently used vulnerability models generally do not provide for the propagation of uncertainty. As a result, the analyst may have to propagate uncertainty by other means. For example, Monte Carlo techniques in which specific values are selected from a range of values for each input parameter could help to map out the uncertainty in the output. It may also be possible to conduct simplified vulnerability calculations in which the uncertainty is mathematically propagated.

To implement any system of quality quantification, it is necessary to adopt a mathematical model of quality/uncertainty. Two such models are currently under consideration.

One of the more promising, rigorous ways to define quality is based upon the statistical concepts of accuracy and confidence. First, based upon the confidence attributed to other information that is used in the supported decision processes, we choose a confidence level. (Commonly, values such as 80%, 90%, 95%, and in extreme cases 99% are used.) Then, one evaluates a vulnerability datum and establishes an

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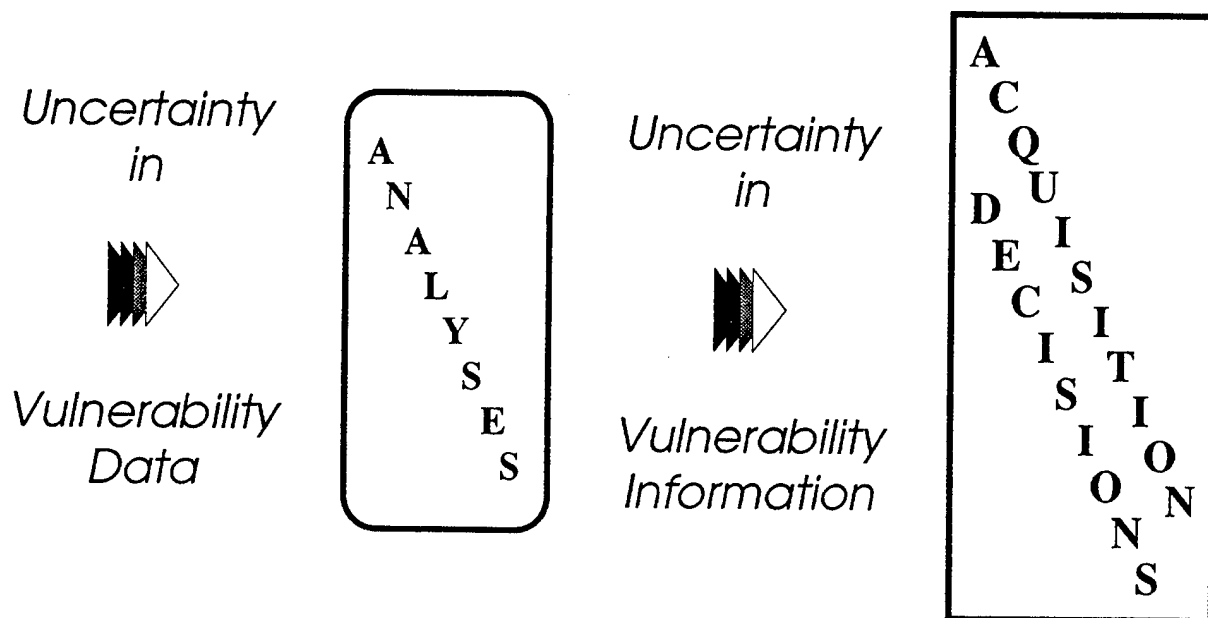
Figure 13. A generic model of vulnerability information generation.

interval within which that datum is believed, at the specified level of confidence, to lie. Such an interval is called a confidence interval; clearly, its width depends not only upon the nature of the datum being estimated, but on the associated level of confidence. For example, suppose that the decisions being supported require a confidence level of 80%. The single shot kill probability (SSKP) for a given round against the subject target is to be estimated. In addition, an interval is specified around that SSKP value such that, with 80% confidence, the true SSKP is believed to lie within the interval. The width of the interval reflects the accuracy of the estimate; the confidence (80%) reflects the adequacy of the interval.

A second promising approach to estimating confidence intervals uses the mathematical tools popularly known as "Fuzzy Math" or "Fuzzy Logic." In one application of Fuzzy Math, the exact value of a parameter is acknowledged as unknown; however, the actual parameter value is believed to lie within a specified range. As shown in Figure 14, a larger, encompassing range is also identified, outside of which the parameter value is most certainly believed not to lie. These ranges form a trapezoidal region, sometimes called a "Membership Function," that describes the uncertainty in the parameter's value. Some

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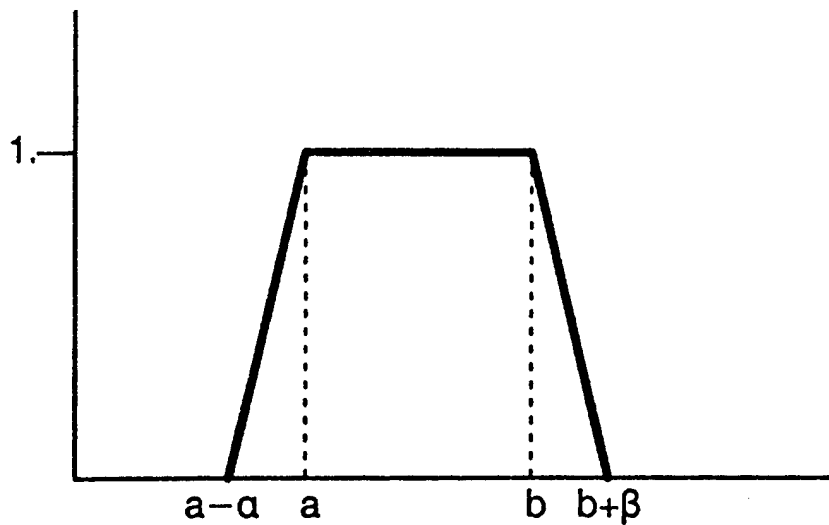
Figure 14. <u>A typical membership function.</u>

current effort is being directed toward application of Fuzzy Math constructs toward the uncertainty in (gridcell level) vulnerability data and the use of Fuzzy Math tools to the aggregation of that data into an overall quality value for a data set (Schlegal, Shear, and Taylor 1985; Taylor and Boswell 1989; Celmins 1993).

As discussed in Celmins and in Schlegal et al., an outstanding benefit of the Fuzzy Mathematics approach to the current problem is in the ability to model analyst uncertainty, a quantity that most certainly does not conform to the rules of probability and common statistics. The use of Fuzzy Math precludes the use of many of the powerful tools of conventional statistics. However, this loss is more than compensated by the more accurate depiction of human estimation provided by a membership function. In addition, current work has provided mathematical procedures appropriate to the manipulation of Fuzzy constructs.

The Ballistic Bicycle example that follows originally used two other measures of quality. First, a heuristic metric was proposed in which the importance of each intermediate datum to the RVIS is multiplied by an evaluation (point estimate) of the quality of that datum and summed to give an overall confidence in the RVIS. Also, for the pure full-up excursion, a parametric estimate, assuming a binomial distribution, is demonstrated.

These examples serve to show that the measure of quality need not be fixed in order to apply the benefit/cost methodology and achieve useful results. However, progress in the Fuzzy Math method of quality quantification resulted in its selection for most of the Ballistic Bicycle example, with a parametric (Binomial) analysis used for the totally experimental test plan. Similarly, the F-16 example presents another application of a Fuzzy Math quantification.

Requirement

In the terms developed previously, the quality requirement can be specified in terms of two numbers. First, one must have a required-accuracy value—a number that expresses the bounds within which one expects to find the true value of an estimated datum. Secondly, one must have a certain confidence that the specified bound is actually large enough. Both of these numbers should come from the (most demanding) supported decision processes. In practice, the confidence value is set a priori to be consistent with confidence expressed in the other inputs to the decision. The accuracy requirement is based upon the following axiom:

- Since decisions depend upon many inputs, such as future scenarios, which cannot be tested, the vulnerability data need not be "perfect." However, confidence in decisions should not be degraded by (testable) inaccuracies in the vulnerability information.

Thus, the quality requirement is totally determined by the supported decision processes, as it should be. Methods for obtaining confidence and accuracy numbers include:

- Quantitative: Sensitivity Analyses of Decision Models.

- Qualitative: Judgment of Experienced Decision Analysts.

5.2.1.3 Expected Cost. Defining the cost of a data-gathering plan, especially the test portion, is difficult because, for many tests, there is wide latitude in the possible outcomes. Furthermore, there may be a markedly different cost associated with every possible outcome. For example, an unexpected catastrophic event can be significantly expensive, a particularly important point for U.S. Navy (USN) and USAF platforms.

However, well-developed techniques exist for determining an expected cost, a probability weighted average cost that accounts for the unexpected. For example, we can apply some rather standard, first-order concepts as follows:

The expected cost of a test is the probability of a given outcome times the cost of that outcome, summed over all outcomes. The expected cost of data-gathering, $\bar{C}$, is the expected cost of one test summed over all tests.

$$\bar{C} = \sum_{i=1}^{NTEST} \sum_{j=1}^{OUTCOMES} P_{ij}C_j$$

P_{ij} : The probability of outcome j in test i.

C_j : The cost to the program of outcome j.

5.2.2 The Benefit/Cost Procedure. Given the concepts listed previously, the procedure for evaluating the benefit/cost ratio of an information gathering plan is summarized in the following sections.

5.2.2.1 Enumerate the RVIS. List the vulnerability information being supplied to the most demanding decision process.

5.2.2.2 Establish the Required Quality for the Decisions to be Supported.

(1) Determine the confidence that is commensurate with the other inputs and analyses in the decision process.

(2) Determine the accuracy necessary in the vulnerability information to assure that the correctness of the decision will not be influenced by uncertainty in the vulnerability data.

(3) In general, select the most demanding accuracy and confidence.

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5.2.2.3 Evaluate the Current (Baseline) Quality of the RVIS.

(1) Adopt one or more procedures, appropriate for the various data, for evaluating data quality.

(2) Evaluate the baseline RVIS quality.

Given that the baseline is insufficient:

5.2.2.4 Construct and Evaluate Data-Gathering Plans.

(1) Analyze the baseline to determine the data that is needed to improve the RVIS quality.

(2) Develop test plans to acquire needed data.

(3) Evaluate expected RVIS quality with data anticipated from test plans.

(4) Evaluate expected cost of test plans.

5.2.2.5 Compare Cost-Effectiveness of Plans. This procedure is demonstrated in a simplified example ("The Ballistic Bicycle") in section 5.2.3.

5.2.3 The Ballistic Bicycle. In order to demonstrate the procedure evolving as the knowledge-based benefit/cost methodology, consider a simple, hypothetical case.

The "Ballistic Bicycle" (Figure 15), being considered for acquisition, is approaching MS II. The bicycle design has not been finalized. However, from concept designs and previous bicycle development programs, a number of features are roughly known. These have been used (and refined) since MS 0 to conduct analyses that have guided the development, with increasing detail included in the analyses as it has become available. Now, approaching MS II, it is necessary to put together a vulnerability-data-gathering plan to assure that the RVIS needed for future design and acquisition decisions will be available when needed.

The subsequent sections correspond to the procedure elements listed in section 5.2.2.

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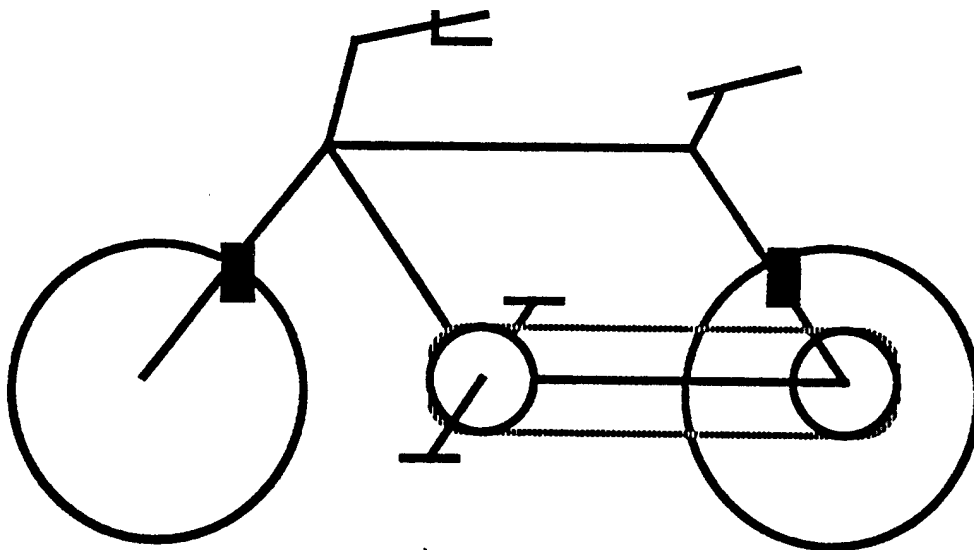
Figure 15. The Ballistic Bicycle.

5.2.3.1 Enumerate the RVIS: List the Vulnerability Information Being Supplied to the Most Demanding Decision Process.

In general, the scenario in which the Ballistic Bicycle will be used is, like the future world situation, most uncertain. However, the decision to buy the bike will hinge largely on a need for such bicycles in training films to be used in Third-World countries. It was noted that grenade attacks in such films invariably involve a bicycle innocently propped up near the doorway of the attacked building. Since this scenario is rather well developed, we take this as the most demanding in terms of concomitant accuracy and confidence. The only threat weapon which will enter into this example is a hand grenade, a fragment and blast threat. Typical delivery accuracy for the grenade is in the order of a 6 m CEP.

Thus, for this example, the data required is the single round kill probability (SRKP) for a thrown grenade (CEP = 6 m) against the Ballistic Bicycle.

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5.2.3.2 Establish the Required Quality for the Decisions to be Supported.

(1) Determine the confidence that is commensurate with the other inputs and analyses in the decision process.

In an actual application of this methodology, the first step in establishing a quality requirement for vulnerability information is to analyze the decision processes which will use the information. Forced to work in an environment of gross uncertainty regarding future scenarios and other decision inputs, decision makers have traditionally not given much formal attention to the degree of confidence that they have in their data. However, it is reasonable to believe that analysis of past decisions and assessment of decision models can lead to a confidence requirement for the vulnerability information. For this example, we take 80% as the confidence value to be met.

(2) Determine the accuracy necessary in the vulnerability information to assure that the correctness of the decision will not be influenced by uncertainty in the vulnerability data.

Similarly, although decision makers have traditionally not given much formal attention to the accuracy of their input data, analysis of past decisions, assessment of the decision models, and an evaluation of the expected accuracy of other inputs can lead to an accuracy requirement for the vulnerability information. For this example, we take .15 (i.e., ±7.5%) as the accuracy requirement.

(3) In general, select the most demanding accuracy and confidence.

The previous factors establish the RVIS quality requirement: the quality must be equivalent to an 80% confidence that the true SRKP for the grenade against the Ballistic Bicycle probably lies within an interval of .15.

5.2.3.3 Evaluate the Current (Baseline) Quality of the RVIS.

(1) Adopt one or more procedures, appropriate for the various data, for evaluating data quality.

In evaluating the quality of the RVIS, it appears that one can take either the confidence or the accuracy as the fixed parameter and evaluate the other.

For the Fuzzy Math analysis, the collected data are of the form: "Give me the range within which you think the true value of the datum "probably" lies. Give me the extremes outside of which the datum "surely" doesn't lie." (The quantification of "probably" and "surely" as 50% and 99% confidence bounds and the calibration of respondents are discussed in Appendix A.) Thus, we are fixing the confidence level and determining how large the corresponding intervals must be in order to claim an 80% confidence that the true SRKP is contained therein. (The interpolation to an 80% confidence is also presented in Appendix A.)

(2) Evaluate the Baseline RVIS Quality.

In the Baseline case (state of knowledge at MS II), the best means of evaluating the SRKP for the Ballistic Bicycle is via an analytical technique such as FULL SPRAY* in which independent blast and fragment vulnerabilities are combined to produce a combined blast-fragment kill assessment.

For the Fuzzy Math exercise, a simplified Full-Spray-like analysis was performed. A simplified, FORTRAN code was written to combine the data and to propagate the uncertainties; the methodology and code are described in Appendix B. (Simplifications include ignoring air drag on the (single mass) fragments. Barrier penetration was not considered important for a bicycle.) The relative importance of the blast and fragment kill mechanisms need not be assumed; they are intrinsically taken into account by the (Survivor-Rule) procedure in the code, which assumes independent effects. Blast-fragment synergism was not addressed.

Evaluation of the Baseline RVIS quality begins with an analysis of the state of knowledge of fragment and blast vulnerabilities at MS II.

Recall: The issue for the knowledge-based benefit/cost evaluation methodology is not whether a datum is known at MS II. Rather, the issue is, How well will a datum be known when it will be needed? Thus, identification of the precise components that will make up the final Ballistic Bicycle may not be relevant. More relevant is, Will good estimates of the vulnerability of those components be possible when they are identified?

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* Computer Program for General Full Spray Materiel MAE Computations, Volume I—User Manual, JMEM Report, 61 JTCG/ME-79-1-1.

The following text will extensively reference Figures 16 and 17. The former portrays a grid on the Ballistic Bicycle which will be used for enumeration and calculation of fragment data. Blast data (assumed azimuthally isotropic) will be enumerated by miss distance, as portrayed in the latter.

The status of pertinent data at MS II is shown in Table 3. In the table, pertinent data is broken into confidence in component values and confidence in ability to predict synergistic effects. In the latter portion of the table, the number-letter combinations refer to Figure 16.

In each case, the data is expressed as a (qualitative) point estimate of confidence and as a range of (Fuzzy Math) values for fragment kills. The Fuzzy Math values (α, a, b, and β) refer to single fragment Pk/h.

The (hypothetical) rationale for the numbers in Table 3 is as follows. In general, there is good capability to predict the effects of fragments on tubular components. A need for data is anticipated for specialized components, such as brake calipers, which have not yet been finalized at MS II. The ability to predict synergistic effects is worse than the ability to predict component damage. (An example of a synergistic effect occurs in grid cell 4C in which a fragment that strikes the brake caliper could leave the caliper undamaged, yet rotate the caliper into the spokes such that the bicycle is left immobile.)
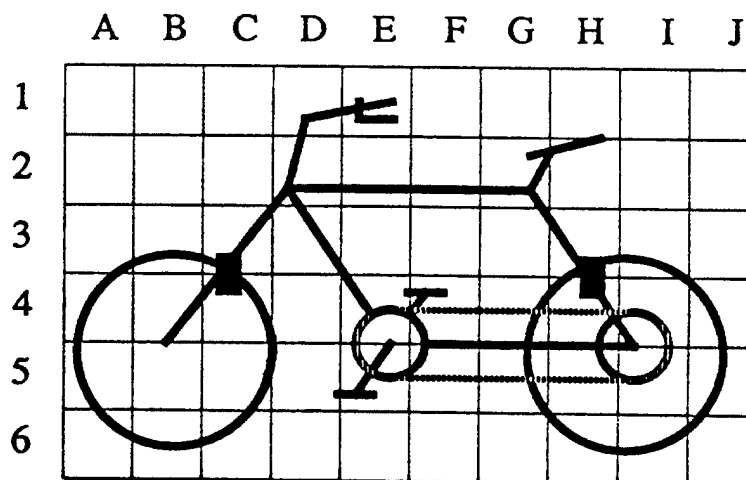
Figure 16. The Ballistic Bicycle: fragment grid.

Ballistic Bicycle
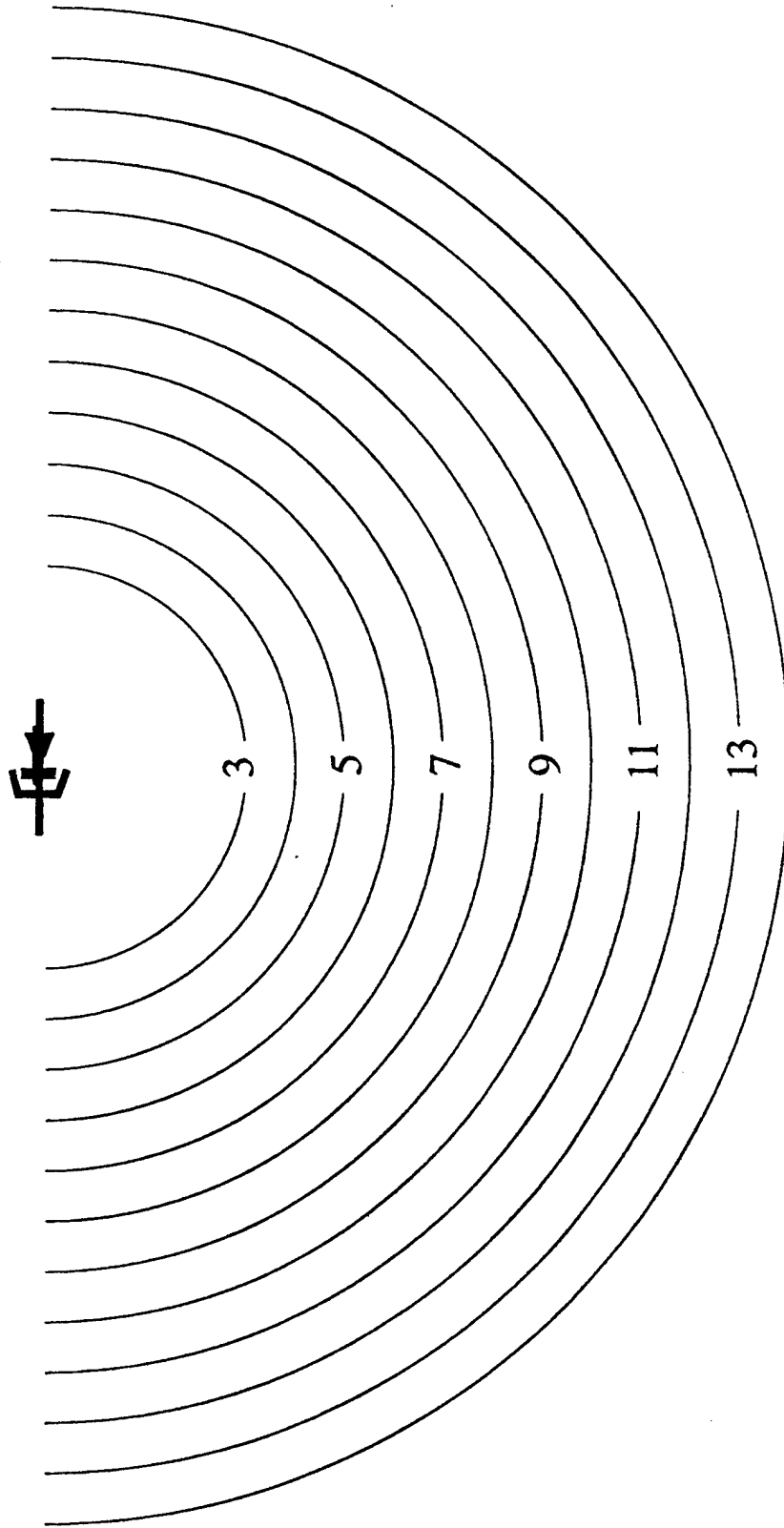
Figure 17. The Ballistic Bicycle: blast grid.

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Table 3. Status of Data: MS II

Component P_k					
Component	Confidence	α	a	b	β
Tubular	Good	.05	.8	.9	.05
Brake Levers	Good	.05	.45	.5	.05
Brake Cables	Fair	.1	.7	.9	.1
Brake Calipers	Poor	.2	.3	.7	.1
Seat	Poor	.0	.0	.0	.0
Spokes	Fair	.1	.2	.5	.1
Sprocket	Poor	.2	.2	.7	.1
Chain	Poor	.2	.3	.8	.2
Wheel	Poor	.1	.4	.9	.1
Synergistic P_k					
Grid Sq.	Confidence	α	a	b	β
1E	Good	.0	.0	.1	.1
3C	Poor	.2	.2	.5	.2
3H	Poor	.2	.2	.5	.2
4C	Poor	.2	.2	.6	.2
4E	Poor	.1	.1	.4	.3
4F	Good	.0	.0	.2	.2
4H	Poor	.1	.2	.6	.4
5H	Poor	.1	.2	.5	.3
Blast P_k					
Miss Dist (m)	Confidence	α	a	b	β
3	Good	0.	1.	1.	0.
4	Good	0.05	0.80	0.95	0.05
5	Fair	0.2	0.60	0.80	0.2
6	Poor	0.3	0.50	0.65	0.3
7	Poor	0.2	0.20	0.50	0.3
8	Poor	0.15	0.15	0.30	0.3
9	Fair	0.1	0.10	0.15	0.2
10	Fair	0.05	0.05	0.1	0.1
11	Good	0.02	0.02	0.05	0.05
12	Good	0.	0.	0.01	0.02
13	Good	0.	0.	0.	0.
14	Good	0.	0.	0.	0.

Using these values and the code described in Appendix B, an estimate of the quality of the current (baseline) vulnerability information was obtained. In that analysis, the Fuzzy SRKP was found to be:

$$\text{SRKP} = 0.59, 0.76, 0.89, 0.92.$$

In accordance with the gauge established in Appendix A, this corresponds to an 80% confidence interval of 0.21. Since this corresponds to an uncertainty of about 25%,[*] we conclude that a data-gathering plan is needed to meet the requirement of the RVIS.

It was also of interest to investigate the relative contributions of the blast and fragment contributions to the result. The structure of the code allowed easy substitution of zeroes for blast and fragment vulnerability. Using this technique gave:

SRKP	$a - \alpha$	a	b	$b + \beta$	"80% int."	"% unc."[*]
Total	0.59	0.76	0.89	0.92	0.21	25
Blast Only	0.29	0.41	0.54	0.71	0.24	51
Frags Only	0.54	0.72	0.88	0.90	0.23	28

From the above, we note that blast alone is about two-thirds as effective as fragments alone.

5.2.3.4 Construct and Evaluate Data-Gathering Plans.

(1) Analyze the baseline to determine the data that is needed to improve the RVIS quality.

Analysis of Table 3 shows that the major causes of uncertainty in the results are from the fragments. Thus, test plans that are aimed to improve the quality of the data must anticipate addressing shortcomings in fragment data, particularly on brake components and on synergistically sensitive regions where the brake and motive components are in close proximity with wheel components. Blast data is lacking for the bicycle as a whole (the ability to evaluate "sail area" and translational response is lacking).

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[*] Percentages calculated with respect to the SRKP value that results from using the center values of all Fuzzy inputs. This value differs slightly from the center value of the Fuzzy output. See Appendix C.

Again, note the context of the foregoing analysis. Here at MS II, the actual vulnerability data is not expected to be known since many of the components have not been finalized. Rather, the discussion concerns the ability to know that data when it will be needed for future decisions.

(2) Develop test plans to acquire needed data.

For this example, three different data-gathering plans were formulated that could alleviate the shortcoming in vulnerability data.

Plan 1: Plan 1 involves tests of fragments against components, fragments against subsystems, and blast against the whole bicycle. No "full-up" tests (actual grenade against a full-up bicycle) are included. The purpose of Plan 1 is to improve the data listed in Table 3.

Plan 2: Plan 2 involves tests of fragments against components. However, instead of separate subsystem (fragment) and blast tests, some actual grenade tests will be used. Like Plan 1, the purpose of Plan 2 is to improve the data listed in Table 3.

Plan 3: Plan 3 embodies an entirely different approach. In it, only actual grenade tests are used. The number of tests will be chosen in order to achieve the required confidence in the (directly measured) SRKP.

The tests to be conducted are listed in Tables 4–6.

Postulate: In Test Plan 1 shots involving blast alone, at the chosen distances (removed from the sure-kill blast region), the bicycle can be protected from permanent damage without loss of kill data. Probability of loss of bicycle = 0.10.

Postulate: Sufficient fragments from the grenade tests will impact the bicycle to allow assessment of synergistic effects. It is believed that the number of possible exposures (12 shots) will compensate for the lack of precisely controlled test conditions.

Table 4. Test Plan 1[*]

	Fragments Only	Blast Only
Components	Brake Calipers Drive Sprockets Chain Wheel	None
Subsystems (by Grid Cell)	3C 4E 4H (2 Series)	None
Full Bicycle (by Miss Distance)	None	5 m 7 m 9 m 11 m

Table 5. Test Plan 2[*]

	Fragments Only	Blast Only
Components	Brake Calipers Drive Sprockets Chain Wheel	None
Subsystems	None	None
Full Bicycle (by Miss Distance)	5 m 7 m 9 m 11 m	

Table 6. Test Plan 3

	Fragments Only	Full-Up Grenade
Components	None	None
Subsystems	None	None
Full Bicycle (by Miss Distance)	4 m (1 shot) 5 m (1 shot) 6 m (1 shot) 7 m (5 shots) 8 m (10 shots) 9 m (6 shots) 10 m (5 shots) 11 m (1 shot)	

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[*] Shots in Test Plans 1 and 2 are replicated three times.

Note: As discussed in section 3, the shot selection in Test Plan 3 is intended to concentrate on the areas of most uncertainty. Since both fragment and blast kills will be intrinsically combined, this area of uncertainty is expected to be displaced outward from the regions of maximum uncertainty of blast or fragments alone.

(3) Evaluate expected RVIS quality with data anticipated from test plans.

In this section, we evaluate the expected quality of vulnerability information that would be available, when needed, should each of the test plans be adopted.

Test Plan 1. As a result of Test Plan 1, the expected improvement in data and the associated change in interval widths is shown in Table 7.

With these Fuzzy values input to the (Appendix B) computer code, the Fuzzy SRKP to be anticipated, if Test Plan 1 were to be adopted, is found to be:

$$SRKP = 0.78, 0.82, 0.87, 0.89.$$

In accordance with the gauge established in Appendix A, this corresponds to an 80% confidence interval of 0.08. Since this corresponds to an uncertainty of about 9%, we conclude that Test Plan 1 will provide adequate improvement to meet the requirement of the RVIS.

We again recall that the *absolute values* of the SRKP are relatively meaningless: At MS II, many of the components haven't even been designed; thus, the center values (the midpoints of the inner, "probable" ranges) of many of the inputs were rather subjective estimates. However, the estimates of future uncertainty, as expressed in the widths of the "probable" and "surely" intervals, are meaningful measures. Hence, the use of the width of the SRKP Fuzzy intervals are useful indicators of expected RVIS quality.

One should note that the SRKP center value anticipated after Test Plan 1 differs slightly from that of the baseline even though the center values of all the inputs were kept unchanged. This, of course, reflects the inherent nonlinearity in a vulnerability code, even one as simple as that of Appendix B. It can similarly be shown that the widths of Fuzzy output intervals can depend, albeit insensitively, upon the

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Table 7. Anticipated Status of Data: Post Test Plan 1

Component P_K					
Component	Confidence	α	a	b	β
Tubular	Good	.05	.8	.9	.05
Brake Levers	Good	.05	.45	.55	.05
Brake Cables	Fair	.1	.7	.9	.1
Brake Calipers	Good	.05	.45	.55	.05
Seat	Poor	.0	.0	.0	.0
Spokes	Fair	.1	.2	.5	.1
Sprocket	Good	.1	.4	.5	.1
Chain	Good	.1	.5	.6	.1
Wheel	Good	.1	.6	.7	.1

Synergistic P_K					
Grid Sq.	Confidence	α	a	b	β
1E	Good	.0	.0	.1	.1
3C	Good	.1	.3	.4	.1
3H	Good	.1	.3	.4	.1
4C	Fair	.1	.3	.5	.1
4E	Good	.1	.2	.3	.1
4F	Good	.0	.0	.2	.2
4H	Fair	.1	.3	.5	.1
5H	Fair	.1	.25	.45	.1

Blast P_K					
Miss Dist (m)	Confidence	α	a	b	β
3	Good	0.	1.	1.	0.
4	Good	0.05	0.80	0.95	0.05
5	Good	0.05	0.65	0.75	0.05
6	Good/Fair	0.1	0.50	0.65	0.1
7	Good	0.05	0.30	0.40	0.05
8	Good/Fair	0.1	0.15	0.30	0.1
9	Good	0.05	0.10	0.15	0.05
10	Good/Fair	0.05	0.05	0.1	0.05
11	Good	0.02	0.02	0.05	0.05
12	Good	0.	0.	0.01	0.02
13	Good	0.	0.	0.	0.
14	Good	0.	0.	0.	0.

center values of the input data. Thus, since the center values may be subjective estimates, it would be incorrect to emphasize the precise, absolute value of the output uncertainty interval. However, it can also

be shown that the relationship between the input center values and the output intervals is sufficiently insensitive to justify the loose quantitative comparisons that are needed for the benefit/cost application developed here.

Test Plan 2. The improvement over the baseline to be anticipated from Test Plan 2 is shown in Table 8. Note that the use of full grenades in the blast tests in lieu of subsystem tests results in more anticipated data on fragments against components. However, the anticipated improvement in synergistic data was less. In addition, the difficulties involved in the blast measurements and the possible loss of blast data due to (independent) fragment effects resulted in a lower confidence (larger Fuzzy intervals) in some of the blast data.

With these Fuzzy values input to the (Appendix B) computer code, the Fuzzy SRKP to be anticipated if Test Plan 2 were to be adopted is found to be:

$$SRKP = 0.79, 0.83, 0.87, 0.89.$$

In accordance with the gauge established in Appendix A, this corresponds to an 80% confidence interval of 0.07. Since this corresponds to an uncertainty of about 8%, we conclude that Test Plan 2 will provide adequate improvement to meet the requirement of the RVIS.

Test Plan 3. As a result of Test Plan 3, the expected improvement in the SRKP is found to be

$$SRKP = 0.85 \pm 0.06.$$

This result is based upon anticipated (binary) results and a binomial error analysis. The calculation is presented in Appendix D. As with Test Plans 1 and 2, Test Plan 3 satisfies the criterion for adequate improvement.

(4) Evaluate expected cost of test plans.

In order to evaluate the expected cost of the three test plans, some basic costs will have to be hypothesized. These are contained in Table 9.

Table 8. Anticipated Status of Data: Post Test Plan 2

Component P_K					
Component	Confidence	α	a	b	β
Tubular	Good	.05	.8	.9	.05
Brake Levers	Good	.05	.45	.55	.05
Brake Cables	Fair	.1	.7	.9	.1
Brake Calipers	Good	.05	.45	.55	.05
Seat	Fair	.0	.0	.0	.0
Spokes	Good	.05	.3	.4	.05
Sprocket	Good	.1	.4	.5	.1
Chain	Good	.1	.5	.6	.1
Wheel	Good	.1	.6	.7	.1

Synergistic P_K					
Grid Sq.	Confidence	α	a	b	β
1E	Good	.0	.0	.1	.1
3C	Good	.1	.3	.4	.1
3H	Good	.1	.3	.4	.1
4C	Fair	.1	.3	.5	.1
4E	Good	.1	.15	.35	.2
4F	Good	.0	.0	.2	.2
4H	Fair	.1	.3	.5	.1
5H	Fair	.1	.25	.45	.1

Blast P_K					
Miss Dist (m)	Confidence	α	a	b	β
3	Good	0.	1.	1.	0.
4	Good	0.05	0.80	0.95	0.05
5	Good/Fair	0.1	0.60	0.80	0.1
6	Good/Fair	0.1	0.50	0.65	0.1
7	Good/Fair	0.1	0.30	0.40	0.1
8	Good/Fair	0.1	0.15	0.30	0.1
9	Good/Fair	0.1	0.10	0.15	0.1
10	Good/Fair	0.05	0.05	0.1	0.1
11	Good/Fair	0.02	0.02	0.05	0.1
12	Good	0.	0.	0.01	0.02
13	Good	0.	0.	0.	0.
14	Good	0.	0.	0.	0.

Table 9. Basic Costs Associated With Testing

Testing Costs (including Munition, Data Analysis, ...)	
Fragment Test (Setup)	$1,000
Fragment Test (1 Replication)	$100
Blast Test (Setup)	$1,500
Blast Test (1 Replication)	$100
Full-Up Grenade Test (Setup)	$2,500
Full-Up Grenade Test (1 Replication)	$1,000
Cost of Target	
Bicycle Frame	$400
Wheels, each	$100
Brakes	$100
Chain	$100
Drive	$200
Bicycle, Assembled	$1,000

It is also necessary to estimate the probability of loss of a target part in a given test. Consistent with the assumptions made previously, we assume that grenade tests (all of which are against the full bicycle) will have a 50% probability of total loss of the target. All component/subsystem tests have a 90% chance of loss of target item.

Additional probabilities are required for the possible synergistic damage regions, such as grid cell 4C in which various amounts of damage could occur. For this simple example, we will limit the possible damage sets to:

GRID CELL 4C (3 SHOTS)

Only brake damaged, every shot:	0.6
Only frame damaged, every shot:	0.3

GRID CELL 4H (6 SHOTS)

Only brake damaged, every shot:	0.6
Frame, wheel, and chain damage:	0.3

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In Tables 10, 11, and 12, target costs are presented in the form "cost (probability)."

Test Plan 1. Test and target costs reflect three replications.

Test Plan 2. Test and target costs reflect three replications.

Test Plan 3. Test Plan 3 consists only of a series of full grenades.

5.2.3.5 Compare Cost-Effectiveness of Plans. The LFT knowledge-based benefit/cost evaluation methodology specifies that the data-gathering/test plans only include those that do satisfy the RVIS quality requirement. In this example, all three test plans are acceptably effective. On the other hand, there is a significant cost difference in the three plans. The expected costs of Plans 2 and 3 are 60% and 180% more expensive than Test Plan 1, respectively. The additional costs stem from the use of full-up grenade shots. These costs accrue in two ways. The tests themselves are significantly more expensive than component/subsystem tests, since data requirements are equal to the sum of fragment and blast tests, and safety requirements make each replication quite expensive. In addition, the probability (0.5) of losing the entire bicycle on a shot adds significantly to the overall expected cost. In essence, the full-up grenade shots carry too great a probability of frame damage due to fragments. This damage is expensive, but yields data that is extraneous due to previous knowledge.

5.2.3.6 Discussion of Ballistic Bicycle Results. The preceding section concludes that full-up grenade shots added significantly to the costs of the test plans, pointing out that hypothesized previous knowledge negated the value of much of the data gained. That is, given a different starting knowledge base, the conclusions might have been different.

It should also be pointed out that the Ballistic Bicycle is a very simple target. It has no fuel or ammunition, the impact of which could begin a chain of reactions. In addition, it is "flat:" components do not screen each other. This flatness also reduces the potential for complex synergistic interactions: components in a two-dimensional array have fewer close neighbors than do those in three dimensions. This simplicity translates into enhanced confidence in a model-based analysis of the vulnerability of the Ballistic Bicycle: the possible existence of "unknown unknowns" is not a factor in the confidence ascribed to the vulnerability analysis.

Table 10. Test Plan 1

Component	Test Cost ($)	Target Cost ($)	Total (All Repl) ($)
Fragments Only			
Brake Calipers	1,300	300(.9)+0(.1)	1,570
Drive Sprocket	1,300	600(.9)+0(.1)	1,840
Chain	1,300	300(.9)+0(.1)	1,570
Wheel	1,300	300(.9)+0(.1)	1,570
3C	1,300	300(.6)+1,200(.3)+0(.1)	1,840
4E	1,300	300(.9)+0(.1)	1,570
4H (2 series)	1,300	600(.6)+3,600(.3)+0(.1)	2,740
Blast Only			
Four Ranges (12 shots)	2,700	12,000(.1)+0(.9)	3,900
Total			16,600

Table 11. Test Plan 2

Component	Test Cost ($)	Target Cost ($)	Total (All Repl) ($)
Fragments Only			
Brake Calipers	1,300	300(.9)+0(.1)	1,570
Drive Sprocket	1,300	600(.9)+0(.1)	1,840
Chain	1,300	300(.9)+0(.1)	1,570
Wheel	1,300	300(.9)+0(.1)	1,570
Full Grenades Only			
Four Ranges (12 shots)	14,500	12,000(.5)+0(.5)	20,500
Total			27,050

Table 12. Test Plan 3

Component	Test Cost ($)	Target Cost ($)	Total (All Repl) ($)
Full Grenades Only			
Full Series (30 shots)	32,500	30,000(.5)+0(.5)	47,500
Total			47,500

The conclusion to be drawn from the previous observations is that each new item of equipment introduces its own relationship between a priori knowledge, item complexity, and experimental costs. It is not possible to make a categorical statement about the benefit-vs.-cost of any class of testing that will pertain to every potential item.

5.2.4 Summary of the Knowledge-Based Benefit/Cost Evaluation Methodology. In summary, the benefit/cost evaluation methodology is based upon the following principles:

(1) The goal of analysis is to provide information for decision makers.

(2) The reason for testing is to provide data that are needed to improve analyses. Since there are many data-gathering techniques, each offering benefits in quality of data and carrying its own price, it is necessary to assemble a data-gathering plan that uses whichever techniques are beneficial to obtain data of sufficient quality at a cost that is low relative to other plans.

To implement this methodology, it is necessary to show that:

• Quality of data can be quantified and related to testing.

• Decision making can be related to quality of vulnerability information.

• Expected costs can be estimated.

To quantify the quality of data, a number of techniques appear to be useful. In this report, we have emphasized one in which data is represented by intervals in which the data provider feels the true value lies. These intervals are amenable to quantitative interpretation in terms of accuracy and confidence.

To relate decision making to vulnerability information, the methodology concentrates on the RVIS that will be used by decision makers. Since this is normally supplied through models, the relationship between data quality and model output is directly applicable to meeting decision needs.

The appropriate cost measure is an expected cost that reflects the probability of large costs accruing from unintended outcomes of tests. The use of expected costs is common in other fields.

The (hypothetical) "Ballistic Bicycle" demonstrates several features of the benefit/cost evaluation methodology. In the example, three methods of quantifying data quality were used. In each case, the quality was propagated into the RVIS. A number of test plans were then proposed, which involved different mixes of component, subsystem, and full-up munition tests; each of the test plans was refined to meet the RVIS quality requirements. Finally, through analysis of expected costs, the preferred plan became obvious. In addition, analysis of the example showed that the conclusion was dependent upon the relationship between a priori knowledge, item complexity, and experimental costs.

It is important to note that the benefit/cost evaluation methodology does not completely eliminate subjectivity. The fact that this analysis must be made early in the development cycle of a system precludes the total elimination of subjectivity. However, it is clear that this methodology:

- Identifies the remaining subjectivities.

- Supports bounding those subjectivities and assessing their potential impact.

- Directly relates the subjective elements to possible testing.

The benefit/cost evaluation methodology offers several ancillary benefits.

- It requires that a global, coordinated data-gathering plan be assembled and analyzed early in the development cycle.

- It requires that confidence and accuracy in both data and analytical results be evaluated.

- It takes advantage and augments analyses that are already an intrinsic part of every system development.

5.3 Knowledge-Based Application to the 23 mm vs. F-16 (1981).

5.3.1 Introduction.

Scope

The Ballistic Bicycle example provides an understanding of the knowledge-based benefit/cost methodology—particularly an appreciation of the flexibility in choices of vulnerability methodologies and quality quantification techniques. However, it remains to be shown that the technique can be applied to an actual case. For this reason, an application of the knowledge-based benefit/cost methodology was made to the F-16 Fighter Aircraft—in particular, to the vulnerability of the F-16 to direct hits by 23-mm high-explosive incendiary (HEI) rounds.

In order to keep this overall report unclassified and yet expose all assumptions and data, some of which are classified, it was decided to augment this report with a classified supplement. This section will therefore contain only unclassified discussions of assumptions, procedures, and relative results such as percent reductions in confidence intervals.

IT MUST BE NOTED THAT THIS STUDY IS NOT AN ACTUAL LFT WAIVER ANALYSIS.

The purpose of this exercise is to scope the level of difficulty to be encountered in the application of the knowledge-based benefit/cost methodology to an actual system. The values used were derived from sources as identified in the classified supplement to this report. In an actual LFT waiver analysis, such resources as are available to the system project manager—who is ultimately responsible for any waiver request—should be used. In addition, this study represents less than 80 man-hours of effort—primarily by analysts not in the fixed-wing aircraft survivability community. It is indisputable that a dedicated effort by appropriately placed analysts would derive data that differ somewhat from those presented here; such data may lead to conclusions that are quantitatively different from those presented in this study.

It must also be noted, however, that the exposure of all data and assumptions, as presented here and in the classified supplement, is an integral part of the knowledge-based benefit/cost methodology. Thus, any differences in conclusions will be directly relatable to differences in specific assumptions and data.

In general, such differences are testable. Thus, in principle, a determined application of the knowledge-based benefit/cost methodology must converge to a single set of conclusions.

Background

In 1981, a manual analysis of the vulnerability of the conceptual F-16 was accomplished by analysts at the Aeronautical Systems Division, Wright-Patterson Air Force Base (WPAFB) (Lentz, Bennett, and Cramer 1981). The availability of this evaluation and its similarity to those that could have been done in the MS II time frame of the F-16 made it an ideal basis for applying knowledge-based benefit/cost methodology. The evaluation considered the six principle (orthogonal) aspects of an aircraft, which encompassed the characteristics of the F-16 as understood at the time of analysis. For each aspect, the silhouette of the aircraft was drawn. Superimposed upon the silhouette were the regions which contained critical components of the aircraft. These regions were identified by the salient critical component contained (see Tables 13–17). However, each region may have included additional critical components. An example is the cockpit region, which, in addition to the pilot, contains other flight-critical components not specifically listed in the table.

The presented area of each region was determined by reference to drawings, similar components in other aircraft, and analysts' expertise. In addition, the presented area ascribed to each region was expanded to account for the fragment spray and blast region associated with a 23-mm HEI projectile.

In 1984, subsequent to the previous analysis, the JLF test series began. In response, a plan for the testing of aircraft was developed by the Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS). In a 1984 report (JLF 1984), an extensive series of component and subsystem level tests are proposed, including a cost estimate for testing categorized into the following subsystems:

- Fuel (including fuel ingestion damage).

- Propulsion (including fuel ingestion tolerance).

- Flight Controls.

Table 13. Critical Regions, Top

Region Number	Major Vulnerable Component	Associated Subsystem
T1	Pilot	Crew Station
T2	Ammunition Drum	Ammunition Drum
T3	Flight Control Computer	Misc. Flight Instruments
T4	Hydraulic Reservoirs	Hyd. Res., Acc., and Lines
T4A	Hydraulic Lines	Hyd. Res., Acc., and Lines
T5	Leading Edge Actuator	Actuators and Lines
T6	Flaperon Actuators	Actuators and Lines
T7	Horizontal Tail Actuators	Actuators and Lines
T8	F-1 Fuel Tank	F1 Fuel Tank
T9	F-2 Fuel Tank	F2 Fuel Tank
T10	Reservoir Tanks	Reservoir Fuel Tank
T11	A-1 Fuel Tank	A1 Fuel Tank and Lines
T11A	Fuel Feed Line	A1 Fuel Tank and Lines
T12	Engine	Engine and Accessories

Table 14. Critical Regions, Bottom

Region Number	Major Vulnerable Component	Associated Subsystem
B1	Pilot	Crew Station
B2	Flight Control Computer	Misc. Flight Instruments
B3	Pitch Rate Gyro	Misc. Flight Instruments
B4	Normal Accelerometer	Misc. Flight Instruments
B5	Leading Edge Actuator	Actuators and Lines
B6	Hydraulic Reservoirs	Hyd. Res., Acc., and Lines
B7	Flaperon Actuators	Actuators and Lines
B8	Horizontal Tail Actuators	Actuators and Lines
B8A	Hydraulic Lines	Actuators and Lines
B8B	Bleed Air Lines	Actuators and Lines
B9	F-1 Fuel Tank	F1 Fuel Tank
B10	F-2 Fuel Tank	F2 Fuel Tank
B11	Reservoir Tanks	Reservoir Fuel Tank
B12	A-1 Fuel Tank	A1 Fuel Tank and Lines
B12A	Fuel Feed Line	A1 Fuel Tank and Lines
B13	Engine Accessories	Engine and Accessories

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Table 15. Critical Regions, Left Side

Region Number	Major Vulnerable Component	Associated Subsystem
LS1	Pilot	Crew Station
LS2	Flight Control Computer	Misc. Flight Instruments
LS3	Normal Accelerometer	Misc. Flight Instruments
LS4	Leading Edge Actuator	Actuators and Lines
LS5	Flaperon Actuator	Actuators and Lines
LS6	Rudder Actuators	Actuators and Lines
LS7	Hydraulic Accumulators	Hyd. Res., Acc., and Lines
LS7A	Hydraulic Lines	Hyd. Res., Acc., and Lines
LS7B	Bleed Air Lines	Hyd. Res., Acc., and Lines
LS8	Ammunition Drum	Ammunition Drum
LS9	F-1 Fuel Tank	F1 Fuel Tank
LS10	F-2 Fuel Tank	F2 Fuel Tank
LS11	Reservoir Tanks	Reservoir Fuel Tank
LS12	A-1 Fuel Tank	A1 Fuel Tank and Lines
LS13	Engine	Engine and Accessories
LS14	Engine Accessories	Engine and Accessories

Table 16. Critical Regions, Right Side

Region Number	Major Vulnerable Component	Associated Subsystem
RS1	Pilot	Crew Station
RS2	Flight Control Computer	Misc. Flight Instruments
RS3	Normal Accelerometer	Misc. Flight Instruments
RS4	Pitch Rate Gyro	Misc. Flight Instruments
RS5	Leading Edge Actuator	Actuators and Lines
RS6	Flaperon Actuator	Actuators and Lines
RS7	Rudder Actuators	Actuators and Lines
RS8	Hyd. Acc. - Vertical Tail	Hyd. Res., Acc., and Lines
RS8A	Hydraulic Lines	Hyd. Res., Acc., and Lines
RS9	Ammunition Drum	Ammunition Drum
RS10	F-1 Fuel Tank	F1 Fuel Tank
RS11	F-2 Fuel Tank	F2 Fuel Tank
RS12	Reservoir Tanks	Reservoir Fuel Tank
RS13	A-1 Fuel Tank	A1 Fuel Tank and Lines
RS13A	Fuel Feed Line	A1 Fuel Tank and Lines
RS14	Engine	Engine and Accessories
RS15	Engine Accessories	Engine and Accessories

Table 17. Critical Regions, Front and Rear

Region Number	Major Vulnerable Component	Associated Subsystem
F1	Pilot	Crew Station
R2	Rudder Actuators	Actuators and Lines
R3	Engine	Engine and Accessories

- Hydraulics.

- Structure.

- Armament.

- Crew Station.

- Miscellaneous/Unique.

- Rotor/Drive Train.

The previously referenced reports (Lentz 1981; JTCG/AS 1984) formed the basis for the data used in this example application. In addition, significant help was provided by Mr. Ralph Lauzze, WPAFB; Ms. Lisa Woods, Booz-Allen Hamilton, Inc.; and Mr. Robert Walther, Dr. James Walbert, and Mr. William Keithley, ARL/SLAD.

5.3.2 Application of Methodology.

Quality of Vulnerability Information

Tables 13–17 list the 66 regions, over six aspects, that were deemed critical (Lentz 1981). In the original (as reproduced in the classified supplement to this report), each region has an associated "Adjusted Presented Area," "Average Region (Pk/h)," and a "Vulnerable Area," which was the product of the first two values. These values were removed here to allow an unclassified presentation of this work. However,

it is important to recognize their existence, since it was the "Average Region (Pk/h)" that formed the basis of the benefit portion of this example.

Tables 13–17 also contain a column entitled "Associated Subsystem." This association, made as part of this example, will be explained next.

Before proceeding with this example, it is important to understand the "manual" analysis described in the JLF document (JTCG/AS 1984). For each of the regions in Tables 13–17, the vulnerability of all components in the region were considered. The analysts used their expertise to gauge the probability of component damage given a hit in the region, from the listed aspect, by a 23-mm HEI round. The analysis included assessment of the standoff (the distance between the probable detonation point and each component) and the probable shielding, as well as the susceptibility of the components themselves. Also included, in a rather subjective way, was an allowance for the chance that an unforeseen event would take place; this allowance was based upon the complexity of the region as well as upon the expert judgment of the analysts. This information was all rolled up into a single number for each region, the "Average Region (Pk/h)." To determine the Pk/h, the probability of target kill given a hit on the region attributable to each major component in the region was estimated. If one component dominated the region, its kill probability was used as the region Pk/h; or else, an average of the kill probabilities of the major components was used. The final value was then adjusted (upward) to account for synergistic effects (i.e., those target kills that cannot be attributed to a single component).

The present knowledge-based benefit/cost analysis focused on the uncertainties associated with the "Average Region (Pk/h)." To quantify the benefit of various test plans, an adaptation of the "Fuzzy Math" technique was used. Using an expert from the Air Systems Branch (ASB) of the ARL, the Pk/h assigned to each entry in Tables 13–17 was "Fuzzified" (i.e., each single value was replaced by two ranges of values: one range in which the real Pk/h probably lies—as judged by the ASB expert, and a larger, encompassing range in which the value most certainly lies). These ranges correspond to the 50% confidence interval and the 99% confidence interval described in the preceding sections of this report. These ranges were then propagated through the manual methodology, resulting in a "Fuzzy" total vulnerable area (i.e., a vulnerable area expressed as a 50% confidence interval and a 99% confidence interval). These were combined into a single 80% confidence interval as described in the preceding sections.

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In addition to placing a range of uncertainty around each Pk/h, the ASB expert was also asked to think about the elements in each region that contributed to the uncertainty. With that in mind, the analyst defined two sets of tests to address that uncertainty, one involving only component and subsystem tests, and one involving full-up LFT. Finally, the analyst estimated the reduction in uncertainty (expressed as reduced sizes for the confidence intervals) given that: (a) the subsystem tests alone were completed, and (b) that the full-up LFT was done in addition to the subsystem tests.

To simplify the previous procedure, it was noted that, although Tables 13–17 contain 66 entries, the regions and associated components could be placed into 10 categories. These are listed in Table 18. Table 18 also lists the number of shots included in each test category in order to achieve the reduction in uncertainty assigned by the ASB expert.

At this point, it is important to note the coarseness of the test solutions presented in this example. Clearly, there are an infinite number of possible shots; hence the reduction to only three possibilities (a fixed subsystem series, a fixed LFT series plus the subsystem series, or no tests at all) is obviously a simplification. However, recall that the purpose of this example is to demonstrate the feasibility of the method. Just as the use of aeronautical engineers from the manufacturer of the F-16 was unwarranted for this example, so is the consideration of a fine tuning of the test series. Moreover, as shown next, the 59,049 combinations of test possibilities evaluated in this study were significantly more than would normally be considered.

With the above data, the 80% confidence interval associated with the total vulnerable area was found to be:

- 0.359 (35.9%) – Baseline (no testing)

- 0.199 (19.9%) – All subsystem test series done; no LFT

- 0.120 (12.0%) – All test series (LFT and subsystem) done.

Table 18. Test Categories

Test Category	Shots Subsystem Series	Shots Live-Fire Series
Crew Station	8	4
Ammunition Drum	5	2
Misc. Flight Instruments	8	4
Hyd. Res., Acc., and Lines	6	3
Actuators and Lines	8	4
F-1 Fuel Tank	10	5
F-2 Fuel Tank	10	5
Reservoir Fuel Tank	10	5
A1 Fuel Tank and Lines	10	5
Engine and Accessories	6	3

At this point, the major set of calculations were performed. All combinations (59,049) of the three possibilities (a fixed subsystem series, a fixed LFT series plus the subsystem series, or no tests at all) for each of the 10 test categories were considered, and the 80% confidence interval associated with each combination was computed. These were combined with the associated costs as described next.

Costs

Equally specialized is the area of assigning costs to the various options. The following section describes the method used for this example. However, it must be noted that, were this an actual live-fire waiver analysis, many resources would be used which were not invoked for this example. Again, the purpose of this example is to demonstrate the feasibility of the method.

It must also be noted that, in making estimates, one generally envisions a range of values rather than a crisp number. (That is, in fact, the basis of the "Fuzzy Analysis" described in the preceding sections.) The estimation of costs, likewise, leads to a range of values and estimation techniques. In such a case, it is common to consciously skew all estimates to favor one course of action so that—if that course of action should still prove cost-ineffective—the course may confidently be excluded. In this example, we have skewed the estimates to favor the LFT series. Thus, in those cases in which the LFT series prove cost-ineffective, the result will not depend upon a subjective assignment that was unfavorable to LFT.

For the estimation of subsystem test series costs, adjustments to an existing set of estimates were made. As listed previously, JTCG/AS (1984) contains the estimates made in 1984 for subsystem level test series for the F-16. These costs include:

- Program planning.

- Design of replica targets.

- Procurement or manufacture of replica targets.

- Pretest preparation of test articles.

- Conduct of the tests.

- Munitions/weapons.

- Data acquisition and reduction.

- Documentation.

- Unique administrative costs.

The subsystem level tests from JTCG/AS (1984) were easily mapped onto the test categories listed in Table 18. Thus, a baseline set of costs was available. These costs, for each test category, were then increased in two ways. First, the cost of the subsystem test series in each category was multiplied by a factor (1.34) to convert 1984 costs to a common (1993) base (Norton 1993). In addition, although "conduct of tests" and "munitions/weapons" were included in the JTCG/AS (1984) costs, the number of shots in each series was not given. Hence, in order to account for the particular number of shots prescribed by the ASB expert to achieve the associated uncertainty reduction, an additional $25k per shot was added to the already specified costs. Although this procedure may be "double-counting" the expense associated with each shot, it is in keeping with the LFT-favoring skew described previously.

The values used in this example are listed in Table 19.

Table 19. Subsystem Costs

Test Category	Subsystem Series Cost ($)
Crew Station	570k
Ammunition Drum	295k
Miscellaneous Flight Instruments	1.2k
Hyd. Res., Acc., and Lines	685k
Actuators and Lines	434k
F1 Fuel Tank	2.85k
F2 Fuel Tank	2.85k
Reservoir Fuel Tank	2.85k
A1 Fuel Tank and Lines	2.85k
Engine and Accessories	850k

In evaluating the LFT costs, it is essential to recall that the knowledge-based benefit/cost methodology being applied here specifies the use of *expected costs*, as described in the preceding sections. Calculation of *expected costs* requires estimates of probable outcomes of firing, as well as the costs associated with each outcome. In this case, two possibilities were considered for each test category. First, the probability of total loss of the target was assessed. For this assessment, the probability of total loss of the target, given that the region was killed, was assessed to be either high (0.8), medium (0.4), or low (0.02). Then the probability of total loss from any shot was taken to be the Pk/h for the region times the high, medium, or low resultant total loss probability.

If the target was a total loss, the cost of the test was assessed to be the cost of the target plus a $50k assessment for the cost of an LFT shot. In keeping with the LFT skew, the cost of the target was taken as the *production cost* as presented by Lauzze and Griffis (1993).

If the target is not lost, the cost of an LFT was assessed to be the cost of the shot ($50k) plus the cost to return the target to its preshot condition. Based upon extensive LFT done by the ARL, multiplied by the relative cost of an F-16 to the costs of the ARL targets, a figure of $400k was assessed for the post shot repair to be applied to all nontotal-loss shots.

The total loss probabilities and resulting expected costs used in this example are listed in Table 20.

Table 20. Expected Cost Data

Test Category	Total Loss Probability	Live-Fire Series Cost ($)
Crew Station	0.02	3.6M
Ammunition Drum	0.64	30.3M
Miscellaneous Flight Instruments	0.02	3.6M
Hydraulic Reservoirs, Accumulators, and Lines	0.36	26.2M
Actuators and Lines	0.02	3.6M
F1 Fuel Tank	0.56	65.6M
F2 Fuel Tank	0.70	81.2M
Reservoir Fuel Tank	0.66	76.8M
A1 Fuel Tank and Lines	0.66	76.8M
Engine and Accessories	0.32	24.0M

Using this data, the expected costs for all 59,049 combinations of the three possibilities (a fixed subsystem series, a fixed LFT series plus the subsystem series, or no tests at all) for each of the 10 test categories were calculated.

5.3.3 Results. For completeness, it is necessary that this example be carried through to the analysis of results. However, as stressed previously, the values used in this example were obtained without recourse to many of the resources that would be available to a program manager who would be evaluating the advisability of an LFT waiver. In addition, this example only discusses one of many possible threat munitions. Hence, the application of these results to the actual test plans for the F-16 is certainly not warranted.

Clearly, the presentation of 59,049 sets of benefit/cost/test plan triads is problematic. To cull out the best options, a cost-effectiveness figure, defined as confidence-interval reduction per dollar, was calculated for each of the 59,049 test plans. The resulting sets of cost-effectiveness/benefit/cost/test plan were then sorted in order of most to least cost-effective. From this list, it is an easy matter to extract the most cost-effective means of achieving each level of certainty in the vulnerability data. These most effective test plans are presented in Table 21 results and are plotted vs. cost in Figure 18. In Table 21, the test plan is presented as a sequence of 10 digits, indicating the test status of each of the ten test categories as listed in Tables 18, 19, and 20. For example, test plan 2222212223 consists of subsystem level tests ("2") for
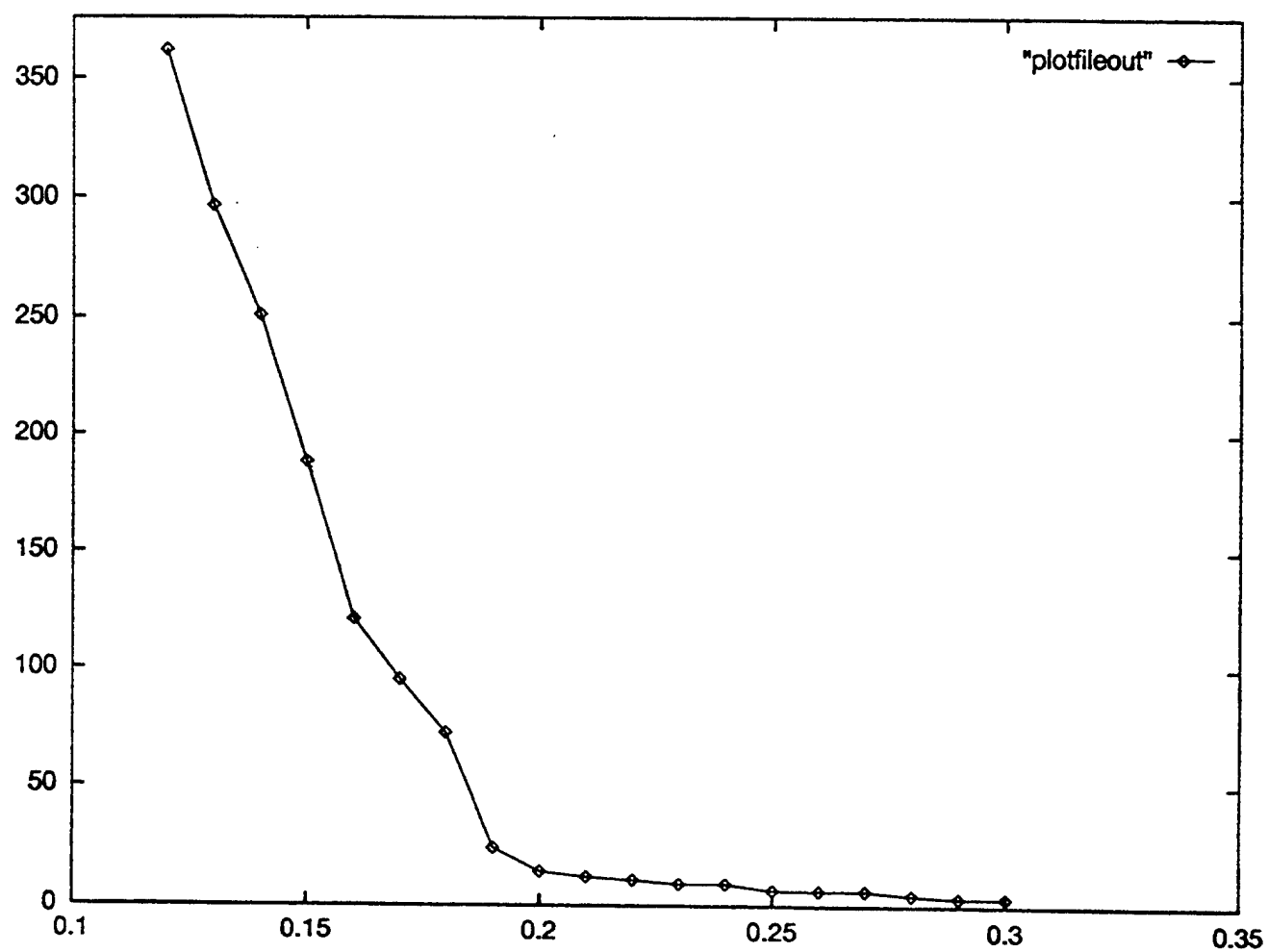
Figure 18. Cost vs. 80% confidence interval.

Table 21. Most Effective Test Plans

Width of 80% Conf. Int.	Cost-Effectiveness	Cost ($M)	Test Plan
.359	******	0.00	1111111111
.30	0.0211	3.42	2111111121
.29	0.0211	3.42	2111111121
.28	0.0173	4.56	2211111122
.27	0.0172	6.27	2111111221
.26	0.0172	6.27	2111111221
.25	0.0166	6.56	2211111221
.24	0.0142	9.12	2111112221
.23	0.0142	9.12	2111112221
.22	0.0130	10.70	2211212222
.21	0.0124	11.97	2111122221
.20	0.0112	14.23	2212222222
.19	0.0064	26.23	3232322222
.18	0.0023	76.43	3233322223
.17	0.0019	99.43	3122322232
.16	0.0016	127.03	3232322233
.15	0.0011	195.43	3212222333
.14	0.0009	261.03	3212232333
.13	0.0007	307.63	3223323333
.12	0.0007	361.70	3233333333

all test categories except category 6 (F-1 fuel tank), which is not tested ("1"), and category 10 (engines and accessories), for which both subsystem and LFT are done ("3").

For the remainder of this discussion, we will use the 80% confidence interval, listed in Table 21 and plotted in Figure 18, as a measure of the uncertainty in the vulnerable area, the information being used in decisions (productions, modifications, tactics, etc.) regarding the subject aircraft. The choice and definition of the 80% confidence interval as the measure of uncertainty was an analyst's decision. Clearly, the "Fuzzy" outputs from the analysis are a direct, detailed measure of the uncertainty; the choice of one particular confidence interval, based upon those Fuzzy outputs, is largely a matter of taste.

Note, also, that the chosen confidence interval encompasses the whole range. That is, an uncertainty of 20% corresponds to ±10%.

Were this an actual benefit/cost analysis, the analyst would now be in a position to rate the various test plans and to draw some conclusions regarding which tests should be done. For example, Figure 18 shows that reducing the uncertainty in the vulnerable area down to 19–20% is quite cost-effective. Referring to Table 21, the reduction in the uncertainty per dollar is in the order of 1.0% per million dollars. (The reduction from 0.359, the starting uncertainty, to 0.2 could be accomplished with a test plan costing $14.2M.)

However, reductions below 19% become very expensive. For example, the cost of reducing uncertainty to 15% is $195M; the payoff (reduction in uncertainty) is only 0.1% per million dollars. A more critical view is to look at the differential cost of the reduction below 20%: To gain the extra 5% reduction in uncertainty costs $181.2M ($195.4–14.2M) or a payoff of only 0.03% per million dollars. The reason for this behavior is clear. In this example, uncertainty reductions below 19% require increasing amounts of LFT, which carry a relatively high expected cost.

The area around 19% uncertainty is, in this example, a grey, transitional area. It is not possible to approach 19% reduction without any LFT: the Test Plan 2222222222, comprising all subsystem tests, only provides a reduction to 19.95%. In addition, Test Plan 2222222222 requires the detailed subsystem testing of components such as the miscellaneous flight instruments, which have a low presented area and high cost. As a result, the differential cost of improvement from 20% to 19.9% is $1.2M or $0.08 per million dollars. Thus, should small improvement below 20% be required, it is equally cost-effective to conduct limited full-up LFT on high profile areas that have a relatively low expected cost. For example, shots into the crew station have a relatively low probability of causing complete loss of the target. Such shots may address many of the "unknown-unknowns" and were thus assessed by the ASB expert as providing moderate reduction in the uncertainty of the crew station Pk/h beyond those provided by subsystem tests. Since the crew station also represents a significant fraction of the critical presented area from five of the six aspects, it is reasonable to expect LFT of this region to be among the first to enter into a cost-effective test plan.

On the other hand, note that LFT of the ammunition drum, in this example, never appears in Table 21. For this region, the low presented area and high probability of total target loss outweigh the gain in uncertainty: such tests are not cost-effective.

The previous observations provide insight to the reasons for the results that evolved in this example. The dominant factor in the cost-effectiveness of a test plan is its expected cost. This, in turn, is driven by the probability of total system loss and the cost of a system. Thus, a similar analysis on a less costly system should show LFT to be more cost-effective than was shown here. Similarly, shots on a system that are unlikely to cause total loss tend to have a markedly lower expected cost and thus higher cost-effectiveness. The complexity of the region under attack also plays an influential role. A complex region is generally felt to contain more opportunities for "unknown-unknowns" and, hence, realize more uncertainty reductions from LFT. And, finally, the size of a region plays the role of an overall weighting factor, since it appears as a multiplier in all outputs related to vulnerable area. Thus, a relatively inexpensive target, whose complex regions are large and unlikely to be catastrophically killed, may be a prime candidate for LFT tests.

5.3.4 Conclusions. IT MUST AGAIN BE NOTED THAT THIS EXAMPLE DOES NOT CONSTITUTE AN ACTUAL LFT WAIVER ANALYSIS.

The purpose of this exercise was to scope the level of difficulty to be encountered in the application of the knowledge-based benefit/cost methodology to an actual system. As stated in the introduction to this section, this example represents less than 80 man-hours of effort—primarily by analysts not in the fixed-wing aircraft survivability community. In an actual LFT waiver analysis, such resources as are available to the system project manager would be brought to bear. While the level of expertise and availability of knowledge would therefore be higher, it is also true that the level of detail—especially in the analysis of vulnerability data and the diversity of potential test plans—would also be higher. Thus, while we conclude that application of the knowledge-based benefit/cost methodology to an actual system is certainly tractable, we anticipate that the expenditure of only 80 man-hours is probably a lower bound.

This example, in conjunction with the Ballistic Bicycle example presented in preceding sections, demonstrates the kinds of conclusions that can be supported through a knowledge-based benefit/cost analysis.

The inputs to the analysis were technical judgments, based upon previous test experience with other targets, details of the subject target which would be emerging at MS II, and tests on the subject target conducted prior to the analysis. These inputs included:

- Available MS II vulnerability analyses.

- Estimates of uncertainties in the inputs to such analyses.

- Conceptual test plans, geared to address those uncertainties.

- Estimated costs of those test plans, including probable outcomes of each plan.

The outputs in this example included total and differential gains accruing from many possible test plans.

In the original statement of the knowledge-based benefit/cost methodology, the requirement for a given level of confidence in the vulnerability information was to be met by an assessment of the decision processes which use the resultant vulnerability information. That is, a goal in uncertainty reduction was to be established a priori and test plans formulated to meet that goal. This example illustrates another approach to the justification of test plan selection. Figure 18 provides a graphical realization of the cost of certainty in vulnerability information. Having conducted such an analysis, one is in a solid position to demonstrate the marginal gain vs. cost, thus imposing reasonable limitations to the expectations of the decision makers.

5.4 <u>Aircraft Attrition-Based Methodology</u>. Section 5.4 is provided by Mr. Ralph W. Lauzze II of the Vehicle Subsystems Division (WL/FIV), USAF, WPAFB, OH.

Reducing combat system losses (attrition) is a primary objective of any aggressive vulnerability reduction program. If the results of LFT can be shown to directly result in reduced attrition, then that savings can be a useful measure of "benefit" in a cost-benefit assessment for LFT. A relatively simple attrition-based methodology, comparing estimated savings due to reduced losses with the estimated cost of executing an LFT program, has been developed. The methodology has been applied to sample cases for aircraft systems and may have utility for evaluating other vehicle classes. The methodology assumes a previously undetected vulnerability "flaw" exists in the system. This causes the system's true vulnerability to be higher than originally assessed. It is further assumed that the flaw is discovered during LFT and subsequently fixed through redesign (and retrofit, if necessary). By comparing the "before" and "after" vulnerabilities, an estimated savings in attrition can be calculated. This savings is then compared

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with the total cost of performing the LFT program, including hardware, test, redesign, and retrofit costs. The methodology is flexible, allowing comparisons to be made for the estimated payoff resulting from the many variations and combinations of options to vulnerability assessment and reduction, ranging from analysis-only to full-up system-level LFT. The sensitivity of the payoff to the various input estimates can easily be made, allowing the analyst to examine a whole range of inputs. This can be particularly useful where confidence in input estimates is lacking. This overall approach to cost-benefit assessment can be beneficial to the planner and analyst in examining where resources could best be applied to assure the most payoff for the LFT investment. It may also be useful to examine the efficacy of pursuing a waiver for system-level LFT.

Several parameters are not currently covered in the methodology, but are being addressed. An important payoff from LFT is improved confidence levels in the subject system's vulnerability or lethality. While not currently included in the methodology, a set of subjective confidence factors could be developed, based on the specific test options of interest, and assigned to the respective cost-benefit calculation in order to "weight" each approach. The cost of crew casualties is not currently included in the methodology; however, estimates could also be developed for incorporation. Also, the impact of Aircraft Battle Damage and Repair (ABDR) is not currently included in the methodology. The costs associated with repairing damaged aircraft and the impact of aircraft that are repaired and returned to combat could also be included. Additionally, the impact of improved operational effectiveness due to increased system robustness (i.e., more tanks killed for fewer system losses, etc.) is not currently, but could be, included.

The methodology consists of the following steps:

5.4.1 Select a Representative Sortie/Threat Scenario. Develop an estimate of the total number of combat sorties, number of aircraft involved, and an "allowable" attrition rate (Probability of Kill given a Sortie - Pk/s). This data is generally available from the planned use of the aircraft and can be compared with similar systems in prior conflicts to gain a historical perspective.

5.4.2 Determine Production/Cost Data for New Aircraft. From manufacturing/production plans, determine the production rate and production cost of the system to be tested. Data on the system's production rate is needed for cases where retrofit is a potential result from the LFT program. Data on the production cost of the system is needed to evaluate replacement costs for systems lost due to combat attrition.

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5.4.3 Establish/Determine Vulnerability Baseline Data. From the system's specifications, determine Pk/h information for the "allowable" attrition for the threat(s) of interest. Determine, for kill levels of interest - generally "K" (loss of control within 30 s), "A" (loss of control within 5 min), "B" (loss of control within 30 min), and "M" (prevention of completing the mission, but not lost from the inventory).

5.4.4 Calculate Estimated Hit Rate (Ph/s). An estimate of the Ph/s can be developed from the allowable attrition rate and the spec values for Pk/h. (Pk/s = Ph/s × Pk/h.) The resulting hit rate can also be compared to existing data to obtain a historical perspective.

5.4.5 Calculate Fraction of the Fleet Lost (FFL). Using the survivor rule, Ph/s, and Pk/h, the FFL can be calculated. Calculate the FFL for the kill levels of interest. (FFL = 1 - [1 - Pk/h × Ph/s] ** Srt, where Srt equals the number of combat sorties per aircraft.)

5.4.6 Calculate DVC. From the FFL, the cost of lost and/or damaged vehicles can be calculated. In order to calculate the total cost of the vehicles, an estimate of the cost of returning damaged systems, deemed to be unrepairable and lost to the inventory, should be included. The DVC is determined by multiplying the percent of the fleet lost by the number of aircraft in the fleet by the cost of each aircraft lost. (DVC = FFL × #A/C × A/C production cost.)

5.4.7 Examine the Benefit of LFT. To estimate the potential benefit of LFT due to reduced attrition, a flaw is assumed to have been overlooked in the design and/or vulnerability analysis of the aircraft. This results in the true Pk/h of the aircraft actually being higher than the assessed spec value. It is further assumed that this true Pk/h is discovered during the LFT program and lowered back to the spec value (or some determined intermediate value) through subsequent redesign (and retrofit, if necessary). By repeating the calculations described in sections 5.4.5 and 5.4.6 (holding probability of hit constant), to obtain a DVC for the true Pk/h, and comparing with the original estimate, a cost savings due to LFT can be assessed.

5.4.8 Estimate Cost of LFT. Estimate the cost of LFT for the options being investigated. The estimate should include all the costs associated with the testing including: the total cost of performing the tests, special facility requirements, and the cost of the test articles required (replicas, components, subassemblies, assemblies, and engineering manufacturing development [EMD] or low-rate initial production [LRIP] or production systems), etc. Because the relationship between cost savings (reduced attrition) and the total investment from the LFT process will be compared, an estimate of redesign costs

and any retrofit costs should also be included. Since the cost of the test hardware, possible redesign, and possible retrofit can be significant, close examination of the actual system acquisition circumstances (availability of hardware, timing with regards to preliminary design review [PDR] and critical design review [CDR], likelihood of retrofit) is required for realistic results. The ability to find and correct the hidden flaw, within the scope of the LFT options being studied, must also be realistic.

5.4.9 Compare Attrition Savings With Cost of LFT. The estimated savings in attrition, from section 5.4.7, can then be compared to the estimated cost of the LFT program as determined in section 5.4.8. The total dollar savings can be compared with the LFT investment and, if desired, the return on investment can be easily calculated. (Consideration should be given to constant year dollars.)

5.4.10 Optimization. Using the steps previously described (sections 5.4.1–5.4.9), an optimum strategy for designing an LFT program can be developed. The most cost-effective strategy for LFT can be ascertained by combining the estimated cost of the various test options with the predicted attrition cost related to the options. Prudent combinations of LFT options including component, subsystem, subassembly, assembly, and system-level testing should be evaluated.

5.4.11 Example. The following is a simple example using the procedure on a hypothetical fighter-type aircraft. The input estimates were selected only to demonstrate the methodology and are not reflective of any current or planned system.

Step 1: Select a representative sortie/threat scenario:

      Total number of combat sorties: 20,000

      Total number of aircraft: 200

      "Allowable" attrition rate (Pk/s): .002 (for K, A, and B kills)

Step 2: Determine production rate and cost of system:

      Production rate (aircraft/year): 50/yr for 4 yr

      Production cost (per aircraft): $40M

Step 3: Determine baseline aircraft vulnerability:

      Pk/h (from hypothetical aircraft specification)

      Pk/h = .3 (for K, A, & B kills)

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Step 4: Calculate estimated hit rate (Ph/s):

Pk/s = Ph/s × Pk/h,

then Ph/s = .0067

Step 5: Calculate FFL:

From survivor rule:

FFL = 1 - [1 - Pk/h × Ph/s] ** Srt

Srt is number of sorties per aircraft: 100

FFL = .18

Step 6: Calculate DVC:

DVC = FFL × #A/C × A/C production cost

DVC = $1,440M

Step 7: Examine benefit of LFT:

Assume true vulnerability:

Say, Pk/h actually .4, discovered and corrected with LFT

DVC (Pk/h = .4) = $1,920M

DVC (Pk/h = .3) = $1,440M

Therefore, savings = $480M

Step 8: Estimate cost of LFT:

For this example:

Option 1 (assembly-level testing only) = $40M

Option 2 (system-level testing complete aircraft, with redesign and retrofit costs included) = $200M

Step 9: Compare attrition savings with cost of LFT:

If the system's Pk/h can be lowered from .4 to .3 using

Option 1, savings = $480M less $40M investment = $440M

Return on investment = 12:1

Option 2, savings = $480M less $200M investment = $280M

Return on investment = 2.4:1

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Step 10: Optimization:

For this example, the optimum approach is apparent; however, more complex evaluations, such as inclusion of component and subassembly testing, redesign without retrofit, etc., can be made using this approach.

Option 1, Total costs = $1,440 (attrition) plus $40M (LFT) = $1,480M

Option 2, Total costs = $1,440 (attrition) plus $200M (LFT) = $1,640M

Conclusion: For this simple example, Option 1 is the most cost-effective approach.

5.4.12 Summary Aircraft Attrition-Based Methodology. In summary, the attrition-based approach has significant merit for evaluating cost vs. payoff for LFT of aircraft. The methodology allows for detail evaluation of the various LFT options; however, care must be exercised in choosing realistic inputs, particularly with regards to test objectives and costs, for the results to be meaningful. It is flexible, relatively simple, and it includes (or has the ability to include) the largest and most important costs and benefits. It exploits the most important cause-effect relationship associated with LFT (i.e., test resources expended result in reduced attrition and saved lives).

5.5 Bayesian Methodology. This section is extracted from the document "Estimating Expected Value of System Testing," written by Stephen M. Robinson from the University of Wisconsin–Madison (Address: Department of Industrial Engineering, University of Wisconsin–Madison, 1513 University Avenue, Madison, WI 53706-1572; email: smr@cs.wisc.edu; fax: (608) 262-8454). The research reported here was sponsored by the U.S. Army Research Office under Grants DAAL03-92-G-0408 and DAAH04-95-1-0149, and by the U.S. Army Space and Strategic Defense Command under Contract DASG60-91-C-0144.

5.5.1 Purpose and Scope. This paper proposes a method for use in estimating the value of LFT of systems or subsystems. It states the assumptions under which the method is proposed for use, explains the procedure and demonstrates it on a small example, and finally considers possible objections and responses to these. The method is intended for use in supporting a decision on whether to request a waiver by the Secretary of Defense of LFT for a particular system on the grounds that LFT is "unreasonably expensive and impractical," under the provisions of the Live Fire Test Law (Title 10, Chapter 139, Section 2366, U.S. Code).

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The effect of the proposed procedure is to estimate the expected value of the information gained from the test, which may help the decision maker judge whether the expense of LFT is or is not "unreasonable." Of course, the decision as to how large a cost increment is "unreasonable" is a matter of judgment, and quantitative analysis methodology cannot replace it. However, such methodology can often clarify the elements of such a decision, and the process suggested here is intended to do so.

The method proposed is based on well-known and widely accepted principles for measuring the value of information. For example, outlines may be found in Raiffa (1978) (section 7.8) and Lindley (1985) (section 7.9), and an expository treatment with several worked examples is in Jackson (1979). However, the particular procedure suggested here in connection with system testing has not, as far as the author knows, been implemented for any real systems, and the example provided is entirely fictitious. Therefore, this paper should be considered as a proposal for further development and testing of the procedure on real systems, rather than as a recommendation for immediate implementation.

5.5.2 Assumptions. The proposed method depends on the following assumptions:

(1) Bayesian statistical methodology, in particular the use of preposterior analysis, is acceptable for use in support of the LFT waiver process.

(2) Costs of a projected LFT can be estimated. In addition, costs of (1) withdrawing the system from the normal development process (after testing, but before deployment) for redesign, and (2) withdrawing the system from the field after deployment (based on failure after deployment, possibly accompanied by loss of life or injury and necessitating recall and/or extensive modification in place) can be estimated.

(3) The effectiveness of the proposed test can be estimated, in the form of probability distributions for system behavior under test conditioned on (unobservable) system characteristics, and the decision to deploy or not to deploy the system depends only on those characteristics.

(4) Expected costs provide a satisfactory measure for decision-making purposes.

For an organization of limited resources facing a potentially extremely costly decision, assumption 4 might not be appropriate; however, for governmental bodies, it is generally reasonable. It is important here because if it did not hold, then it would be necessary to do the cost calculations with utilities instead

of monetary costs. This would increase the difficulty of applying the model, primarily because of practical obstacles to assessing a utility function in the environment under consideration.

5.5.3 Measuring Value Added by Testing. In this section, we describe the proposed procedure. The description is brief and technical, intended only to make precise just what is being proposed. The next section will present a simple example to illustrate the application of the method.

To fix the notation, consider a state space S, points of which specify the underlying (unobservable) system characteristics. These are the things we would really like to know about the system but cannot. In principle, S could be multidimensional and either continuous or discrete. In practice, because of complications in estimating the required data, S should be as simple as possible. In the example, S is a discrete space consisting of 16 points.

We shall refer in what follows to the *critical* region: this is simply the subset of S consisting of those states $s \in S$ that would result in a decision to withdraw the system from service after deployment. Thus, if the system's state lies in the critical region, then the system is to be considered unfit for deployment.

The proposed model would accommodate multiple critical regions, each associated with a different decision; however, we consider here only the simplest case in which the system is either fit for deployment or not.

While S represents the information about the system that we would like to know but cannot observe, another state space T represents test outcomes. For example, one element of T might represent a certain combination of degrees of damage incurred in a specified sequence of trials using specified munitions. We assume that the space T represents all of the possible outcomes of the proposed test. Again, this space could be continuous or discrete, and its points could be of any dimension desired. However, in our example, again for simplicity, we make T a discrete space and in fact put its points in one-to-one correspondence with those of S.

We assume that we have a prior probability distribution $P_S(s)$ for S. This distribution may be continuous or discrete. It may also be diffuse (uniform), indicating complete ignorance of the system's state, or it may include any advance information that we have, for example as a result of analysis and modeling or of previous experimentation.

Second, we assume that we have a conditional probability distribution $P_{T|S}(t|s)$ for test outcomes t given the state s. It is worth noting that the specification of this distribution becomes progressively more burdensome as the sizes of S and T, and the fineness of detail represented in them, increase. For example, if we use discrete distributions with the number of elements in S being σ and the number in T being τ, then the number of conditional probabilities involved is $\sigma\tau$. This number becomes less manageable as σ and τ increase. Therefore, especially when discrete distributions are used, it seems advisable to use the proposed method to gather information about only the most important aspects of the system, rather than as a comprehensive modeling tool.

The final decision to be made about the system is binary: withdraw the system from the acquisition process (for redesign or possible cancellation) or else proceed through the acquisition process. With the first option, we assume there is a specified cost increment $C_R(s)$; note that this cost may depend on s, so that we may face different kinds of costs depending on the state of the system.

If we choose the second option and s does not lie in the *critical region*, then there is no cost increment, since the process is to proceed normally. On the other hand, if we choose the second option and S does lie in the critical region, then there is a "disaster" cost $C_D(s)$; this is understood to include both the costs of withdrawing the system from the field after deployment, or of making emergency modifications to it in place, and any quantification that we may wish to make of the intangible factors associated with system nonperformance (casualties, readiness shortfalls, bad publicity, and so on). In addition to $C_D(s)$, we must also pay, in this case, the rework cost $C_R(s)$.

Recall that the true system state is unobservable; therefore, our decision has to be made under uncertainty. Suppose that at the time of decision we have a probability distribution $p(s)$ over system states; this could be either the prior distribution $P_S(s)$ already mentioned, or another distribution based on additional information (for example, information from testing). In order to fix notation, in the rest of this paper, we assume that we are using discrete distributions, and we use sums; the changes needed if the distributions were continuous would be to replace the sums by integrals.

We make the decision to deploy or not to deploy based on minimizing total expected cost. If we decide not to deploy, this expected cost will just be the expected rework cost, namely

$$EC_o(p) = \sum_s C_R(s)p(s). \qquad (1)$$

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On the other hand, if we deploy the system and s does not belong to the critical region CR, then we pay nothing, whereas, if we deploy, and s does belong to the critical region, then we pay $C_D(s) + C_R(s)$. Therefore, the expected cost associated with deployment is

$$EC_1(p) = \sum_{s \in CR} \left[C_D(s) + C_R(s) \right] p(s).$$

(2)

The total expected cost associated with our decision, given the probability distribution $p(s)$, is then

$$EC(p) := \min \left\{ EC_0(p), EC_1(p) \right\}.$$

(3)

For later reference, we note that each of EC_0 and EC_1 is linear in the probabilities $p(s)$; therefore, the expected cost EC is a concave function of these probabilities.

With these concepts in place, we can specify the procedure that we propose. The basic idea is extremely simple: to compare the expected system costs that we face with and without LFT. The excess of the costs without LFT over the costs with LFT represents the expected value of the information to be gained from the test. The person responsible for requesting the waiver can then use this expected value, together with the predicted cost of carrying out the test itself (which is not included in these calculations), to support a decision on whether to proceed with testing or to request a waiver on the grounds that LFT is "unreasonably expensive and impractical."

To make the calculation, we first calculate the prior probability distribution of the test of the outcomes by

$$P_T(t) = \sum_{s} P_{T|S}(t|s) P_S(s),$$

and then the conditional probability distribution of states given outcomes using

$$P_{S|T}(s|t) = P_{T|S}(t|s) P_S(s) / P_T(t).$$

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If we decide not to perform the test, our expected cost C_N is given by $EC(P_S)$, defined by (3) with the probabilities $p(s)$ being replaced by $P_S(s)$. On the other hand, if we do test and we observe outcome t, then our expected system cost is given by $EC(P_{S|t})$. The prior probability of observing t is $P_T(t)$, so our total expected system cost given a decision to test is

$$C_T = \sum_t EC(P_{S|t})P_T(t).$$

Note that since we assume the test outcomes t to be disjoint and exhaustive, we have

$$P_S(s) = \sum_t P(st) = \sum_t \left[P(st)/P_T(t) \right] P_T(t) = \sum_t P_{S|t}(s)P_T(t),$$

where st indicates the event "s and t." The probabilities $P_T(t)$ sum to 1, so the concavity of the expected cost EC as a function of the probabilities means that $C_N \geq C_T$: that is, if we test, then our expected system cost will not be greater than if we do not test. The savings from testing, namely $C_N - C_T$, can then be compared to the cost of testing to help support a decision on whether to test or to seek a waiver.

5.5.4 Illustrative Example. In this section, we provide an example to illustrate application of the proposed method. This example is a much simplified version of a decision problem involving an aircraft. Our goal is to estimate the value of LFT for this system.

In the example, we consider two types of munitions, rocket (R) and small-arms round (S), that might be employed against the system. If a hit occurs, we suppose the damage can be expressed in terms of one of four categories: catastrophic kill (K), sufficient damage to cause mission abort (A), damage requiring later maintenance but permitting mission completion (C), and negligible damage (N). Of course, a more detailed example could subdivide the aircraft into numerous regions, some more important than others, and could consider the effects of multiple hits in one or more of these regions.

In terms of the previous notation, our state space S has 16 elements, each consisting of two letters selected from the set $\{K, A, C, N\}$: for example, the pair KC indicates that if the aircraft is hit by a rocket we can expect catastrophic kill, but if it is hit by a small-arms round, we can expect a level of damage permitting mission completion.

Table 22 gives our prior (pretest) probability of each state in *S*. We assume the degrees of damage caused by the two different types of munitions are independent, so, for example, the probability of the pair *KC* just mentioned would be (.20) (.35) = .07. This independence assumption is not necessary.

Table 22. Prior Probabilities of System States

Munition	K	A	C	N
Rocket	.20	.35	.40	.05
Small-Arms Round	.05	.10	.35	.50

We shall take the critical region to consist of those states that (1) include a catastrophic kill by either munition, or (2) include a "mission abort" event from small-arms fire. Therefore the noncritical region consists of all those pairs whose first letter is *A, C,* or *N,* and whose second is *C* or *N.* Simple computations using the data in Table 22 show that the prior probability of the systems being in the critical region is .32. The choice of critical and noncritical regions is completely at the disposal of the modeler, and we could have taken any other subset of *S* to be the critical region.

Table 23 gives the conditional probabilities of test outcomes *t*, given true system states *s*. The outcome space *T* actually consists of 16 points, the notation for which is identical to that for the elements of *S.* Therefore, the full table of conditional probabilities has 16 × 16 = 256 entries. However, to reduce the requirements for display of data, we make several assumptions, none of which is necessary to the analysis. First, we assume that for each *s, s´, t,* and *t´,* the events "for the rocket, the true state is *s* and the test outcome is *t*" and "for the small-arms round, the true state is *s´* and the test outcome is *t´* " are independent; this assumption implies independence of *t* and *t´,* as well as our earlier assumption of independence of *s* and *s´,* and under it the probability $P(tt'|ss')$ can be computed as $P(t|s)P(t'|s')$. Second, we assume that the conditional probability of outcome given state is the same for the two types of munitions. Under these assumptions, the full table of 256 probabilities can be recovered from the following 4 × 4 table, in which true system states are shown along the top, and test outcomes along the side.

Table 23. Probability of Test Outcome Given System State

Outcome (below)	K	A	C	N
K	.9	.1	0	0
A	.1	.8	.1	0
C	0	.1	.8	.1
N	0	0	.1	.9

This table indicates that we have considerable confidence in the discriminatory power of our test. Less optimism about the test would have resulted in a more diffuse set of conditional distributions.

From data in Tables 22 and 23, we calculate the prior probabilities of the test outcomes from the relationship

$$P_T(t) = \sum_s P_{T/S}(t|s)P_S(s).$$

Because of the independence assumption, instead of displaying a table of 16 items, we can display in Table 24 two rows of 4 items each, corresponding to the rocket and the small-arms round; the probability of a composite outcome is then found by multiplication, just as it was with the prior probabilities for system state.

Table 24. Prior Probabilities of Test Outcomes

Munition	K	A	C	N
Rocket	.215	.340	.360	.085
Small-Arms Round	.055	.120	.340	.485

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Next we calculate the conditional probabilities of true system states s given test outcomes t, using the formula

$$P_{S|T}(s|t) = P_{T|S}(t|s)P_S(s)/P_T(t),$$

and using the data from Tables 22, 23, and 24. Again, because of independence, we can reduce the amount of displayed data to two tables, one for the rocket and one for the small-arms round. These are shown as Tables 25 and 26. The true system states are at the side, and the test outcomes are along the top. Numbers are rounded where necessary to make the probabilities in a distribution sum to 1.

Table 25. Probability of True System State Given Test Outcome
            (Rocket)

True State (below)	K	A	C	N
K	.8372	.0588	0	0
A	.1628	.8235	.0972	0
C	0	.1177	.8889	.4706
N	0	0	.0139	.5294

Table 26. Probability of True System State Given Test Outcome
            (Small-Arms Round)

True State (below)	K	A	C	N
K	.8182	.0417	0	0
A	.1818	.6666	.0294	0
C	0	.2917	.8235	.0722
N	0	0	.1471	.9278

Now let us suppose for simplicity that the rework cost $C_R(s)$ is \$2B (billion) for each s, and the disaster cost $C_D(s)$ is \$5B for each state s that is in the critical region CR (it is zero for all other states). If we are given some probability distribution $p(s)$ over system states, let us define

$$pCR = \sum_{s \in CR} P(s);$$

this is simply the probability that the system's true state is in the critical region. With the rework and disaster costs just given, the calculations in (1)–(3) become relatively simple. In particular, if we decide not to deploy, we just pay \$2B, so $EC_0(p) = 2$. If we deploy and the system is good (its state s is not in CR), then we pay nothing, whereas, if we deploy and $s \in CR$, then we pay \$7B. Therefore, $EC_1(p) = 7p_{CR}$, and we have

$$EC(p) = \min\{2, 7pcr\}.$$

We shall calculate C_N and C_T by replacing the distribution $p(s)$ by $P_S(s)$ and $P_{S|T}(s|t)$ respectively.

If we do not test, there is a probability of .32 that the system state is in the critical region, so the expected cost will be

$$C_N = \min\{2, 7(.32)\} = \min\{2, 2.24\} = 2,$$

and we will decide not to deploy the system.

In order to determine the expected cost C_T if we decide to test, we first calculate for each test outcome t the probability that the *true* system state s belongs to the noncritical region as defined previously. (We are actually going to use the probability that it is in the critical region, but the complementary noncritical probability is simpler to calculate in this case.) For example, suppose the outcome state is AC. Then from Table 25 the probability that the state with respect to rocket damage is A, C, or N (given rocket test outcome A) is .8235 + .1177 + 0 = .9412. From Table 26, the probability that the state with respect to small-arms damage is C or N (given small-arms test outcome C) is .8235 + .1471 = .9706. Therefore, the probability that we are in the noncritical region, given test outcome AC, is (.9412) (.9706) = .9135. These

probabilities are summarized in Table 27. The outcomes for the rocket are along the side, while those for the small-arms round are along the top.

Table 27. Probability That System Is in Noncritical Region Given Joint Test Outcome

Rocket (below)	K	A	C	N
K	0	.0475	.1580	.1628
A	0	.2745	.9135	.9412
C	0	.2917	.9706	1
N	0	.2917	.9706	1

If we do test, then, for example, consider the possibility that we observe test outcome *KA*. Referring to Table 27, we see there is a probability of .0475 that the system is not in the critical region; hence p_{CR} = 1 − .0475 = .9525, so the expected cost if we deploy the system is 7 (.9525) = 6.6675, while the expected cost without deployment is 2. Accordingly, we will not deploy the system, and our expected cost in case we observe *KA* is 2. By making this computation for each possible outcome, we can see that we will decide to deploy the system in 6 of the 16 possible test outcomes: namely, those for which *t* is given by a pair *XY*, with *X* being *A*, *C*, or *N* and *Y* being *C* or *N*. By referring to Table 24, we can calculate the probability of the event *E* consisting of observing 1 of these 6 outcomes to be .6476, so that the probability of observing 1 of the other 10 outcomes is .3524. In the latter case, we will not deploy the system, and we will pay the rework cost of $2B. In the former case, we will deploy the system, and, as we have seen, our expected cost will be $7p_{CR}$.

For each of the six test outcomes we can calculate the probability p_{CR} that the true system state lies in the critical region by referring to Table 27 and taking the complementary probabilities for those outcomes in which we are interested. We display those in Table 28, along with the probabilities $P_T(t)$ for each of the six outcomes.

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Table 28. Probability That System State Is in Critical Region Given
Selected Outcomes

Outcome t	$P_T(t)$	$P(s \in CR|t)$
AC	.1156	.0865
CC	.1224	.0294
NC	.0289	.0294
AN	.1649	.0588
CN	.1746	0
NN	.0412	0

For each of the six test outcomes t listed in Table 28, the conditional expected cost of the optimal decision (deploy), given that we have observed t, is $7P(s \in CR|t)$. By multiplying this conditional cost by the probability $P_T(t)$, shown in the first column of the table, and adding, we find that the component of total expected cost attributable to observing one of the these six outcomes is .1690. We have previously seen that the conditional expected cost in each of the other 10 outcomes is 2, and the probability that we will observe 1 of those 10 outcomes is .3524. Therefore the component of total expected cost attributable to observing 1 of those 10 outcomes is (2) (.3524) = .7048. As these two groups exhaust the set of possible outcomes, the total expected cost given a decision to test is

$$C_T = .1690 + .7048 = .8738 .$$

Therefore, provided the cost of the test is less than the difference $C_N - C_T$ of \$1.1262B, we would expect to gain by a decision to test.

5.5.5 Possible Objections and Responses. Here we consider some possible reasons that might be advanced against this procedure and provide some responses to these.

(1) *The procedure is complicated, and it requires a lot of numbers.* This is true. However, going through the process of making the cost calculations may cause us to think more about the process and to get better data than we otherwise would. In the process, we may come out with a better

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decision that we would otherwise have made. In addition, the procedure is quite flexible, in that the system states and outcomes considered may be extremely coarse (perhaps only two states, serviceable or unserviceable) or quite detailed, and the work may be adjusted accordingly.

(2) *We may have to guess at a lot of the data.* This is also true. However, the kind of data required here will be required for any rational decision to test or not. Some of it may be estimated from previous tests of the system under consideration, or of other similar systems, or even from such devices as combat simulations. The difference in a "judgmental" decision is that the places where one guesses at data are not visible. An attempt to set out an orderly calculation, as is suggested here, may result in a better-documented case for whatever action is chosen.

(3) *We should be using utilities and not expected monetary value (EMV).* This issue was mentioned at the beginning. The contention here is that EMV is a reasonable criterion for governmental decisions, at least about issues that are unlikely to bankrupt the country. System tests of the kind we are considering here should fit within this framework.

5.5.6 Summary. We have presented a method for estimating the EMV contributed by a decision to test a system and have illustrated its use on a simple numerical example. We have suggested that a systematic decision procedure like the one outlined here may be useful in supporting a decision on whether to seek a waiver of LFT, since the information accumulated during the decision process helps to establish whether LFT would be "unreasonably expensive and impractical."

6. RECOMMENDATIONS AND CONCLUSIONS

This report focuses on the four areas outlined in the Statement of Work for this study. We have detailed the V/L process structure as a framework for describing a simulated target-threat encounter. This taxonomy was developed when the similarities between different ballistic threats (indirect-fire munitions, direct-fire munitions, HEI rounds) against various targets (logistical targets, armored vehicles, aircraft) became obvious. Since the original development, it has been understood that this taxonomy also holds for other threat mechanisms - electronic, chemical, and biological warfare against defense materiel. Using the taxonomy to describe a specific simulation is useful in showing the metrics produced at each level and the methodologies used in the mapping functions.

Models and analysis methods that are to be applied in support of LFT (PMS II) should include information at all stages at which the vulnerability of the system can be affected. Thus, for each threat damage mechanism, a complete set of vulnerability information includes component vulnerability data, subsystem-component interactions (fault trees), and subsystem interactions. Additionally, if damage mechanisms are not independent, combined effects for components, subsystems, and multiple subsystems must be included. For whatever type of model is applied, it is reasonable to assume an uncertainty for each stage of input as well as an uncertainty each time the model aggregates damage among components, within subsystems, and between subsystems (to the system level). The uncertainty associated with aggregation is due to possible dependent effects among various components and subsystems or among various damage mechanisms or both. Different types of information are obtained through a variety of analyses and test procedures, including simulation modeling and nondestructive testing along with component, subsystem, and full-up LFT. The tradeoffs between full-up LFT and other information-gathering plans must address the ability to obtain information at each of these stages.

While agreeing with the spirit of the live-fire law, we realize that information can be substituted for testing. Thus, in attempting to formalize the LFT waiver process, we have outlined a set of four risk-benefit assessment methodologies, each of which is an information-based approach. Each one attempts to determine whether a full-up LFT program for any particular system is "unreasonably expensive and impractical." We emphasize that any formalized methodology should, in its final form, address all types of information and, furthermore, that this information should be of sufficient accuracy and at a sufficient level of confidence such that undetected vulnerabilities would be very unlikely in the systems produced. None of the four methodologies is fully developed, but we are encouraged by the fact that each of them shows promise in contributing to the overall goal of a formalized procedure. The report presents these four methodologies, labeled as follows:

- Decision-Tree Methodology.

- Knowledge-Based Methodology.

- Attrition-Based Methodology.

- Bayesian Methodology.

The decision-tree methodology incorporates a series of questions pertaining to the costs and benefits of full-up LFT of a system. It represents an expert system of sorts in that the answers to the various questions will lead the user on a path that will eventually provide a decision concerning whether or not to apply for a waiver from full-up LFT while simultaneously suggesting alternative testing strategies. This methodology could work well, combined with any of the other approaches, to act as a filter to grant waivers to systems that are clearly unreasonably expensive and impractical, before going into the highly detailed analyses required by the other methodologies.

The knowledge-based methodology is based upon the following principles:

- The goal of analysis is to provide information for decision makers.

- The reason for testing is to provide data that is needed to improve analyses.

- There are many data-gathering techniques, each offering benefits in quality of data and carrying its own price. It is necessary to assemble a data-gathering plan that uses all appropriate techniques to obtain data of sufficient quality at a cost that is low relative to other plans.

In this methodology, vulnerability analysis methodologies currently in use are used to quantify the quality of information.

The attrition-based methodology compares estimated savings due to reduced losses with the estimated cost of executing a full-up LFT program. In the methodology, it is assumed that a previously undetected vulnerability "flaw" exists in the system, causing the system's true vulnerability to be higher than originally assessed. By detecting the flaw through full-up LFT and fixing it through redesign (and retrofit, if necessary), the system vulnerability can be reduced. By comparing "before" and "after" vulnerabilities, an estimated savings can be calculated and compared to the total cost of the full-up LFT, redesign, and retrofit.

The effect of the Bayesian methodology is to estimate the expected value of the information gained from the test. While using probable cost (as does the knowledge-based methodology), the Bayesian methodology also employs probable gain (from an experiment) in establishing a figure for risk-benefit.

Within this report, we have presented examples in applying two of the methodologies (attrition-based and knowledge-based).

All the risk-benefit analysis methods to LFT are still in the early stages of development. Some are more complete than others; but, in fact, it must be understood that the development and application of risk-benefit analysis methods to LFT are still in the research stage. All of the methods presented show sufficient promise to be included in this document. However, each one has shortcomings to be overcome, problems to be solved, and concepts to be proven. The best solution may prove to be a hybrid of the best ideas from all four; the decision-tree methodology, in particular, seems to be compatible with each of the others in that it might serve as a prefilter for arriving at a decision concerning LFT. It may also prove that the needs of the services are sufficiently different and that more than one standard methodology is required.

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APPENDIX A:

QUANTIFICATION OF FUZZY ACCURACY AND UNCERTAINTY

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A.1. "Probably" and "Surely."

The trickiest part of this procedure—whether it is called "Fuzzy math" or not—is understanding the meaning of a Fuzzy datum.

(The reason for putting "Fuzzy" in quotes is because the procedure being presented here uses very little of the large body of work that has evolved under the title "Fuzzy mathematics." The procedure described here requires just enough to make recognition of Fuzzy mathematics an ethical necessity.)

In the following discussion, the word "datum" (plural "data") will refer to values of fundamental quantities—determined from tests, data analyses, or wherever—that are used as inputs to vulnerability models. The term "information" will refer to the outputs of such models. Vulnerability information is subsequently used, in conjunction with other information, by decision-makers.

The problem being addressed is the quantification of uncertainty in the vulnerability information being given to decision-makers. In particular, it is necessary to relate uncertainty in fundamental vulnerability data—as used for inputs to vulnerability analysis models—to the outputs of those models that form the bulk of vulnerability information for decisions.

The approach taken is to present a model of a fundamental input datum, which quantitatively includes the uncertainty present in the datum. This uncertainty is then propagated through the vulnerability analysis models, arriving at a quantitative expression for the uncertainty in the outputs.

The model of an uncertain (Fuzzy) input datum is based upon the following postulates:

1. All data values are ultimately decided by an analyst.

2. Generally, for any given datum, there is a range within which the analyst believes the datum value "probably" lies.

3. Generally, an analyst can state an upper bound above which he/she believes that the datum value surely doesn't lie. Similarly, a lower bound can be stated.

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NOTE WELL: These values have no statistical significance. No attempt is being made to model the distribution of a random variable. Rather, this is merely an attempt to model an analyst's estimation of a single value.

If we were to represent these concepts graphically, using the value "1" to represent a belief in the appropriateness of associated values with the datum, and "0" to represent a belief in the inappropriateness, a model of an analyst's estimate of the value of a datum could be portrayed as in Figure A-1. The purpose of the line connecting the four points is merely as an aid to the eye.

The problem lies in quantitatively interpreting the terms "probably" and "surely" and conveying that interpretation to the analysts whose data and associated confidence is being modeled.
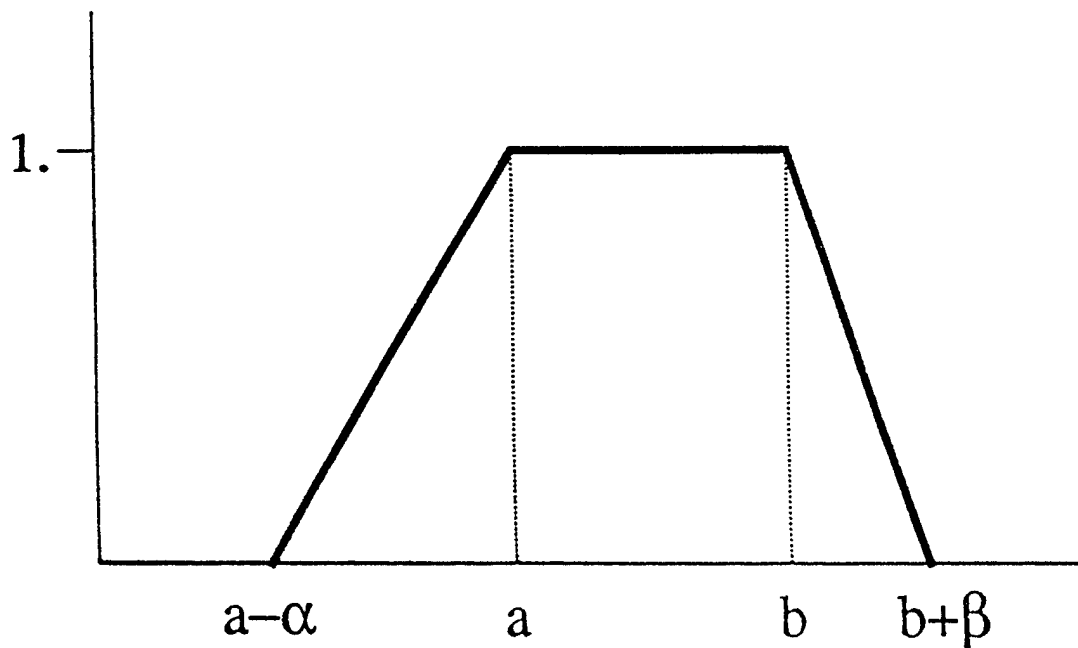

Figure A-1. Model of a datum value estimate.

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Recall that we are not modeling the distribution of the actual values of the datum; rather, we are modeling an analyst's estimate of a single value. Thus, it is appropriate to consider a *gedanken* experiment performed on analysts.

Consider a group of analysts competitively estimating the values of a list of data. Each analyst is to give the range in which he/she believes each datum value to lie. Afterwards, the data are evaluated. For each analyst, the widths of the ranges given for each datum are summed; and the winner is the analyst with the smallest sum. However, any analyst is disqualified who fails to include at least X of the data values within the ranges assigned. Therefore, the optimum strategy would be to assign ranges to the data that are just large enough that the analyst is correct X of the time.

With this model of the estimation process, we can put a quantitative definition on terms such as "probably" and "surely." For example, a possible definition of "probably" is "Let X = 50." The range specified in postulate 2 is thus the smallest range such that the analyst expects more than half of his range estimates to include the actual datum value. Similarly, "surely" could mean "large (small) enough to be correct in 99 out of 100 estimates." In this paper, again, note: We are not attempting to determine the distribution of any variable. Rather, we are attempting to calibrate the "margin of error" that an analyst assigns to the values he/she attaches to disparate data.

For convenience, we will generically refer to the ranges in which values are believed to "probably" and "surely" lie as the "Fuzziness" of a datum. A datum value expressed in terms of such ranges will be referred to as a "Fuzzy number."

A.2. Reduction in Assigned Uncertainty.

Now, consider the role of actual knowledge in this process. Clearly, an analyst must have some knowledge that is pertinent to every datum. In practice, analysts use surrogate information or computations of varying complexity upon which to base estimates.

The availability of a dependable measurement of a datum allows an analyst to reduce its Fuzziness. This is propagated through the analysis into a reduction in the Fuzziness in the final vulnerability information, thus implying greater certainty in the result.

A.3. Interpolation Between "Probably" and "Surely."

Note that, thus far, only four values have been discussed: two that delineate the "probable" region and the two extrema. In terms of expected correct estimates, these were construed to be 50% and 99%. Recalling that these values are subjective regardless of the prior data and experience, it would be naive to attempt a high-resolution calibration of the intervals between the "probable" range and each of the extrema. However, requests for other than 50% confidence are common. Following the procedure outlined previously, it would be possible to ask an analyst to increase the range for each datum estimate such that he/she would expect to be correct 80% of the time, for example. However, it is unrealistic to place the burden of additional intervals upon analysts who have estimated the 50% and 99% confidence intervals for data. Therefore, a scheme is proposed to specify X intervals from the 50% and 99% intervals already derived.

We make two observations:

1. An increase in requested confidence should always require an increase in the width of the associated interval.

2. The required increase in interval per increase in confidence becomes larger as the required confidence approaches 1.

A well-known function that displays these characteristics is the cumulative normal. Having no further information, we propose using the cumulative normal to gauge the size of an interval corresponding to a confidence between 50% and 99%. This gauge is shown in Figure A-2.

NOTE: It must be emphasized that the use of the mathematical function commonly referred to as the "cumulative normal" is strictly an artifice proposed by the author which exhibits the desired characteristics listed previously. Although the cumulative normal function finds frequent application as a probability distribution, no probabilistic implications are being made by its use here.
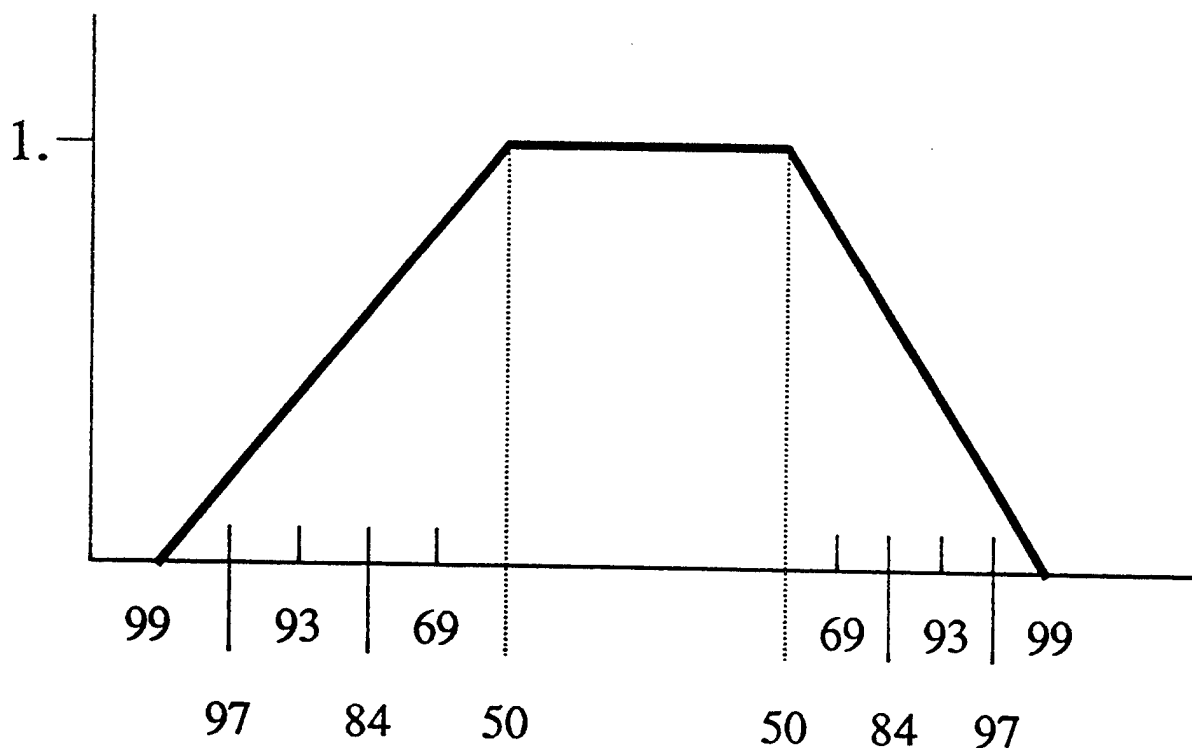
Figure A-2. Model of a "gauged" datum value estimate.

It is also noted that a linear gauge, as implied by a straight line connection between the respective inner and outer values of a Fuzzy number, is commonly used in applications of Fuzzy mathematics. In the present application, the conclusions to be drawn will, in most cases, be relatively insensitive to the gauge chosen to interpolate between the inner and outer intervals of the Fuzzy results.

Thus, referring to Figure A-2, to find an interval that corresponds to the 80% confidence used in the point estimate evaluation, we will take an interval encompassing two-fifths of the space between the "Probably" and "Surely" points.

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APPENDIX B:

METHODOLOGY/CODE FOR EVALUATION OF
SINGLE ROUND KILL PROBABILITY (SRKP)

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In the Fuzzy analysis approach to evaluation of required vulnerability information set (RVIS) quality, it is efficient and desirable to use the same analytical techniques and codes that are already being used in the development of the item. For an area weapon such as a grenade, an analytical technique such as FULL SPRAY[*] is indicated in which independent blast and fragment vulnerabilities are combined to produce a combined blast-fragment kill assessment. For the Ballistic Bicycle example, a Formula Translation (FORTRAN) Code was written that implements the basic concepts of FULL SPRAY. That code is described in this appendix.

(Actually, two codes were written, as discussed in Appendix C.)

First, the single round kill probability (SRKP) depends upon the probability of an incoming round landing at a given radius from the bicycle times the probability that such a round will result in a kill of the target.

$$SRKP = \sum_{RADII} P_H(R) \times P_K(R) \qquad \text{(B-1)}$$

In equation B-1, $P_H(R)$ is an input (the grenade delivery accuracy). $P_K(R)$, the kill given a round at R, depends upon the probabilities of blast and fragment kill. Treating them as independent, we have:

$$P_K(R) = 1 - (1 - P_{K_{Blast}}(R)) \times (1 - P_{K_{Frag}}(R)) , \qquad \text{(B-2)}$$

or, if dealing only with crisp numbers (see Appendix C),

$$P_K(R) = P_{K_{Blast}}(R) + P_{K_{Frag}}(R) - P_{K_{Blast}}(R) \times P_{K_{Frag}}(R) . \qquad \text{(B-3)}$$

In equations B-2 and B-3, $P_{K_{blast}}(R)$ is a fundamental vulnerability input (the traditional "blast curve"). The radii of interest are shown in Figure B-1.

[*] Computer Program for General Full Spray Materiel MAE Computations, Volume I–User Manual, JMEM Report, 61JTCG/ME-79-1-1.
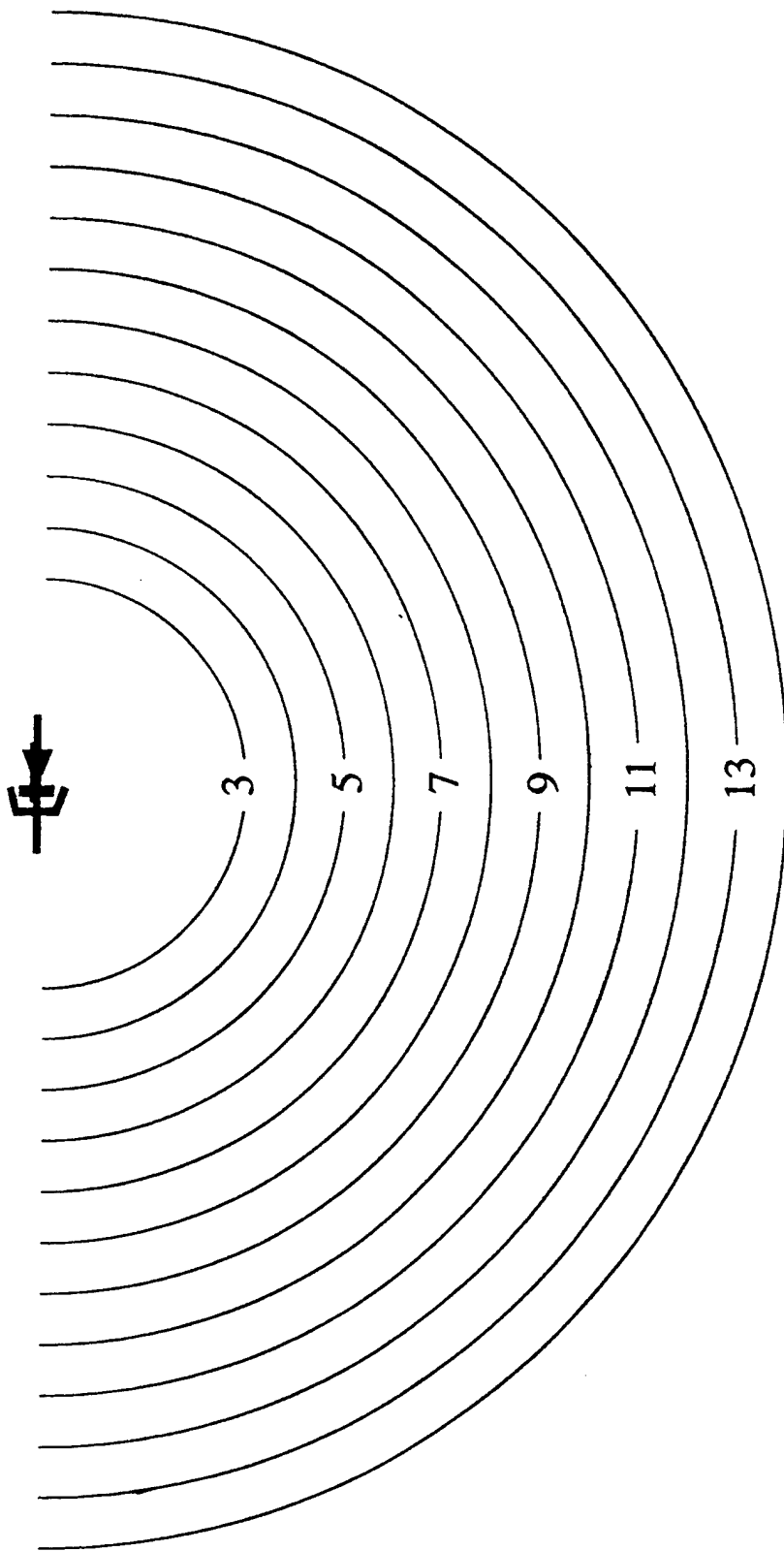
Figure B-1. The Ballistic Bicycle: blast grid.

In this and in most current analyses, only single-cell kills are considered. Therefore, it depends upon the probability of a fragment hitting a grid cell (refer to Figure B-2) times the probability that such a fragment would kill the bicycle. Assuming independence among cells, we have

$$P_{K_{Frag}} = 1 - \prod_{Grid} (1 - P_{H_{Cell}}(R) \times P_{K_{Cell}}). \qquad \text{(B-4)}$$
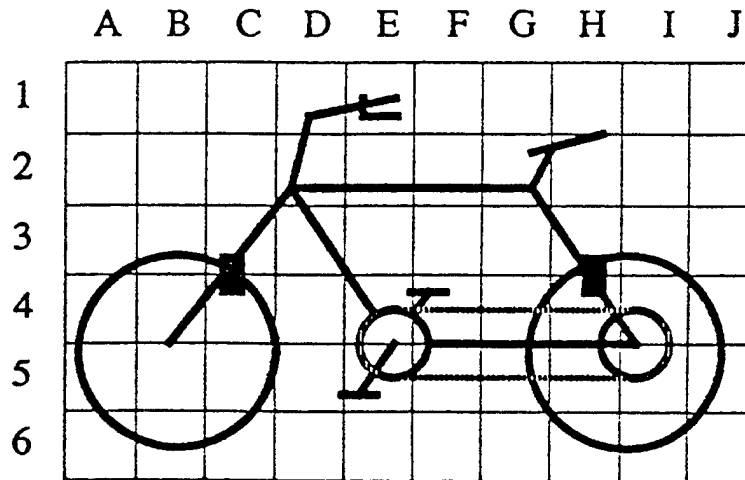
Figure B-2. The Ballistic Bicycle: fragment grid.

Assuming an isotropic distribution of fragments from the grenade, the hit probability of a cell ($P_{H_{Cell}}$) is given by

$$P_{H_{Cell}} = Frags/sr \times \left(\frac{Cellsize}{R}\right)^2 \times I. \qquad \text{(B-5)}$$

Here, *Frags/sr* is the density of fragments per steradian emitted by the grenade, I is the fraction of the cell occupied by the major bicycle components (corresponding to the "Importance" parameter used in the Point Estimate Technique), and *Cellsize* and *R* are expressed in the same (linear) unit.

Returning to equation B-4, $P_{K_{Cell}}$ is assumed to depend upon at most one critical component per cell. In addition, kill probability is accorded to synergistic effects in several cells. (Synergistic cells were also

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used in the Point Estimate Technique.) Assuming independence between synergistic and component failures, we have

$$P_{K_{Cell}} = 1 - (1 - P_{K_{Component}}) \times (1 - P_{K_{Synergism}}).$$ (B-6)

As was the case for $P_{K_{Blast}}(R)$, $P_{K_{Component}}$ and $P_{K_{Synergism}}$ are fundamental vulnerability inputs.

The program that implements the previous equations consists of a main routine and four subroutines. Inputs, all read from files, include:

- $P_H(R)$ Array
- $P_{K_{Blast}}$ Array (Fuzzy)
- $P_{K_{Component}}$ Array (Fuzzy)
- $P_{K_{Synergism}}$ Array (Fuzzy)
- Cell data, which consists of
  - The (major) component in each cell
  - The synergism, if any
  - The occupied fraction of the cell
  - Total number of fragments in the round
  - Cell size (in meters)

Because of the structure of the input data and the association of component and synergistic data with each cell, it is easy to change data values pertaining to components, synergisms, and blast and rerun the SRKP calculation. Advantage was taken of this feature in producing the results presented in the main body of this report.

APPENDIX C:

OBSERVATIONS ON IMPLEMENTATION OF FUZZY MATH IN
CONVENTIONAL COMPUTER CODES

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The definition of the sum of two Fuzzy numbers, P_1 and P_2, is given by:

$$\mu_{P_1 + P_2}(t) = \max_{x+y=t} [\min(\mu_{P_1}(x), \mu_{P_2}(y))] \qquad \text{(C-1)}$$

In Equation C-1, $\mu_{P_1 + P_2}(t)$ is the value of the "membership function" at value t, and $\max_{x+y=t}$ is the maximum for all values of x and y such that $x + y = t$. For simple (trapezoidal) Fuzzy numbers, the interpretation of equation refadd is quite straightforward. Referring to Figure C-1, one sees that the smallest value of t for which the minimum of $\mu_{P_1}(x)$ and $u_{P_2}(y)$ is not zero must be at $a_1 + a_2$. Hence, $a_{1+2} = a_1 + a_2$. Similar reasoning gives the values for b_{1+2}, c_{1+2}, and d_{1+2}.

- $a_{1+2} = a_1 + a_2$.
- $b_{1+2} = b_1 + b_2$.
- $c_{1+2} = c_1 + c_2$.
- $d_{1+2} = d_1 + d_2$.
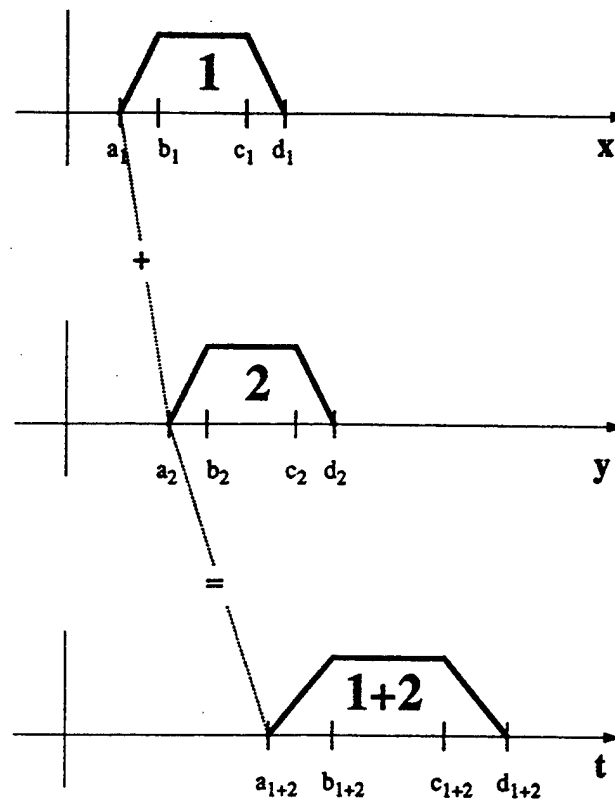
Figure C-1. Fuzzy addition.

Very similarly, multiplication for trapezoidal Fuzzy numbers can be simplified to:

- $a_{1\times2} = a_1 \times a_2$.
- $b_{1\times2} = b_1 \times b_2$.
- $c_{1\times2} = c_1 \times c_2$.
- $d_{1\times2} = d_1 \times d_2$.

Note the extremely handy implications of this result. As long as the only operations being performed are addition and multiplication of trapezoidal Fuzzy numbers, there is no mixing of the respective points of the Fuzzy numbers: lowest values are combined with lowest values, lower middles with lower middles, etc. This implies that a computer code which involves only addition and multiplication can be used for Fuzzy calculations even if the code was written to operate only on crisp (non-Fuzzy) numbers: One need only execute the code four times with four sets of input data corresponding to the lowest value of each datum, the lower middle values, etc.

Unfortunately, this extremely fortuitous simplification does not pertain if other operations (such as Fuzzy subtraction) are included. As seen in Figure C-2, the corresponding rules for subtraction are:

- $a_{1-2} = a_1 - d_2$.
- $b_{1-2} = b_1 - c_2$.
- $c_{1-2} = c_1 - b_2$.
- $d_{1-2} = d_1 - a_2$.

And similarly, division of trapezoidal Fuzzy numbers can be simplified to:

- $a_{1/2} = a_1/d_2$.
- $b_{1/2} = b_1/c_2$.
- $c_{1/2} = c_1/b_2$.
- $d_{1/2} = d_1/a_2$.
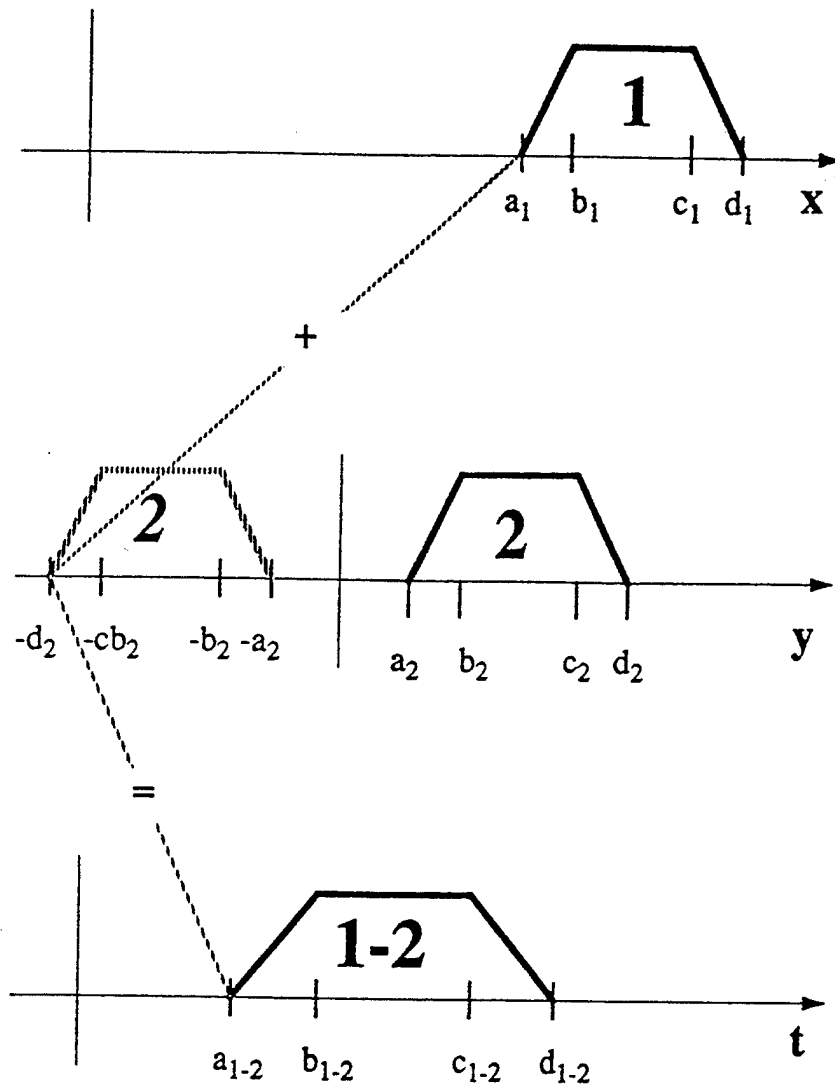
Figure C-2. Fuzzy subtraction.

Note that the previous discussion refers only to those operations involving Fuzzy numbers; scalar arithmetic involved in the code is unchanged, of course.

The savings that could be realized by using current (crisp number) computer codes for Fuzzy analyses are so significant that one is led to investigate how values which are potentially Fuzzy are used in common codes. To this end, the crisp-number version of the simple computer code (about 500 lines) written for the analysis of the Ballistic Bicycle, was analyzed for appropriateness. It was found that the Fuzzy data (blast, component, and synergistic P_Ks) were involved only in addition, multiplication, and in "survivor ruling" of the form:

$$Q = 1 - [(1 - A) \times (1 - B)] \qquad \text{(C-2)}$$

Analysis of Equation C-2 reveals that, in spite of the presence of subtraction, the respective points in the Fuzzy numbers remained unmixed: *both* A and B are reversed before multiplication, and the outer negation restores the order that was switched by the negations inside the parentheses.

[Note, however, that the "Survivor Rule" does not survive the expansion shown in Equation B-3. Were Fuzzy numbers substituted directly into the expansion, the result would be to mix the values. (Subtraction of the product would mix a product of highest values with the lowest values from the first two terms.) In effect, the use of crisp mathematics to expand Equation B-2 violates the rules of Fuzzy mathematics an odd number of times.]

To verify this finding, a second version of the simple Ballistic Bicycle analysis code was written. In this version, all Fuzzy numbers are treated as four-vectors,[*] and all arithmetic is done by subroutines that implement the rules listed previously. As expected, the Ballistic Bicycle results via the second version were identical to those obtained by four runs of the first (crisp) version.

Clearly, this exercise provides no proof that any other common vulnerability code can be used for Fuzzy analyses without modification. However, given that the operations performed for the Ballistic Bicycle are indeed representative of those normally performed, there is reason to further investigate the common codes.

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[*] Actually, five-vectors. In addition to the Fuzzy arithmetic involving the inner and outer intervals, "crisp" calculations were conducted using the mean (center) values of all input variables. The results of these calculations were used as the basis for the evaluation of percentages.

APPENDIX D:

AN EXERCISE IN BINARY TESTING

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The Ballistic Bicycle example required the generation of a hypothetical test plan which involved only "full-up" shots (i.e., shots in which the weapon [a grenade] was employed against a full target [bicycle]). Specifically, the example required an estimation of the confidence/accuracy of conclusions that could be drawn from a test series.

Although just an exercise to generate a hypothetical example, the exercise proved to be illustrative of considerations that must be entertained in the planning of an actual suite of tests. We have therefore included an account of the exercise in this appendix.

In the example, it is stated that the data to be used by the "decision makers" who are being supported by the Ballistic Bicycle study are single shot kill probabilities (SRKPs). We take SRKPs to be given by:

$$SRKP = \int P(r) \times P_k(r) \, dr, \qquad (D\text{-}1)$$

where $P(r)$ is the probability of a grenade hitting the ground at a particular point indicated by r, $P_k(r)$ is the probability of a kill given a hit at r, and the integral is taken over all r.

It was furthermore given that the accuracy of the grenade was characterized by a circular error probable (CEP) of 6 m.

We define the fractional error in SRKP as:

$$\Delta SRKP = \int P(r) \times \frac{\Delta P_k(r)}{P_k(r)} \, dr, \qquad (D\text{-}2)$$

where $\Delta P_k(r)$ is the uncertainty in the probability of a kill given a hit at r. It is this uncertainty that we intend to decrease through Test Plan 3.

The next step in building up this example was to generate uncertainty estimates. For this purpose, we used the binomial distribution as a data generator. In particular, if p is the probability of a kill, then—in N shots—the expected number of kills, $\bar{x}$, is given by

$$\bar{x} = N \times p.$$

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Assuming that the results come from a binomial distribution, the standard deviation in $\bar{x}$ is given by:

$$\Delta\bar{x} = \sqrt{Np(1-p)} \ ,$$

and the fractional uncertainty in the kill probability (p) is given by:

$$\Delta P_k(r) = \sqrt{p(1-p)/N} \ . \tag{D-3}$$

It is also necessary to adopt a test strategy, preferably one that will minimize the cost of the test series. One such strategy is to begin with distant shots that are not expected to damage a target. One systematically moves in until kills begin to occur. At this point, sufficient shots are taken at each point to bring the uncertainty, given by equation D-3, to the desired size before proceeding inward another step. Once reaching the range of sure kills, the series stops.

The uncertainty in the SRKP, given by equation D-2, is then found by multiplying the probability of hitting at each distance from the bicycle—as calculated from the CEP—times the associated uncertainty—given by equation D-3.

The results of this exercise are shown in Table D-1. For each distance, the circular hit probability was evaluated and the kill probability estimated. Then, we determined the number of shots required to bring down the contribution at that miss distance to that overall uncertainty (last column in Table D-1). Finally, the total uncertainty was found by integrating (summing) over the miss distances, as indicated by equation D-2.

Table D-1. Bin Estimation for Test Plan 3

Distance From Target (m)	P(r)	Shots	Kills	p (est.)	Frac. s.d.	dPk(r)*P(r)
6	0.12	1	1	1.000	0.000	0.000
7	0.10	5	4	0.800	0.179	0.018
8	0.09	10	5	0.500	0.158	0.014
9	0.07	6	2	0.333	0.192	0.013
10	0.06	5	1	0.200	0.179	0.011
11	0.04	1	0	0.000	0.000	0.000
12	0.03	1	0	0.000	0.000	0.000
13	0.02	1	0	0.000	0.000	0.000
TOTALS		30	13			0.056

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LIST OF ABBREVIATIONS

ABDR	-	Aircraft battle damage and repair
ACAT	-	Acquisition Category
AFAS	-	Advanced Field Artillery System
ALF	-	Army live-fire
AMSAA	-	U.S. Army Materiel Systems Analysis Activity
ARL	-	U.S. Army Research Laboratory
ASB	-	Air Systems Branch
BAD	-	Behind-armor debris
BDAR	-	Battle damage assessment and repair
BDR	-	Battle damage repair
BVLD	-	Ballistic Vulnerability/Lethality Division
CASTFOREM	-	Combined Arms and Support Task Force Evaluation Model
CDR	-	Critical Design Review
CEP	-	Circular Error Probable
COEA	-	Cost and operational effectiveness analysis
CVG	-	Committee on Vulnerability Guidelines
DOD	-	Department of Defense
DODD	-	Department of Defense directive
DODI	-	Department of Defense instruction
DSVM	-	Degraded states vulnerability methodology
DT&E/ASP	-	Director, Test and Evaluation, Air and Space Program
DT&E/LMS	-	Director, Test and Evaluation, Land and Maritime Systems
DT and OT	-	Development tests and operational tests
DUSA(OR)	-	Deputy Under Secretary of the Army (Operations Research)
DVC	-	Damaged vehicle cost
EMD	-	Engineering Manufacturing Development
EMV	-	Expected monetary value
FFL	-	Fraction of the fleet lost
FORTRAN	-	Formula Translation Code
HEI	-	High-explosive incendiary
JLF	-	Joint live fire

JTCG	-	Joint Technical Coordinating Group
JTCG/AS	-	Joint Technical Coordinating Group on Aircraft Survivability
KE	-	Kinetic energy
LF	-	Live-fire
LFT	-	Live-fire testing
LFT&E	-	Live Fire Test and Evaluation
LOF	-	Loss of function
LRIP	-	Low Rate Initial Production
MNS	-	Mission need statement
MS II	-	Milestone II
NRC	-	National Research Council
ORD	-	Operational requirements document
OSD	-	Office of the Secretary of Defense
PDR	-	Preliminary Design Review
PMS	-	Premilestone
RAM	-	Reliability, availability, and maintainability
RAMD	-	Reliability, Availability, and Maintainability Division
RVIS	-	Required vulnerability information set
SARDA	-	Assistant Secretary of the Army (Research, Development, and Acquisition)
SC	-	Shaped-charge
SDAL	-	Standard damage assessment list
SDIO	-	Strategic Defense Initiative Office
SLAD	-	Survivability/Lethality Analysis Directorate
SOW	-	Scope-of-work
SQuASH	-	Stochastic Quantitative Analysis of System Hierarchies
SRKP	-	Single round kill probability
SSKP	-	Single shot kill probability
STAR	-	System Threat Assessment Report
T&E	-	Test and evaluation
TEMP	-	Test and Evaluation Master Plan
TRAC-WSMR	-	TRADOC Analysis Center at White Sands Missile Range
TRADOC	-	U.S. Army Training and Doctrine Command
VAMP	-	Vulnerability Analysis Methodology Program

VAST	-	Vulnerability analysis for surface targets
V/L	-	Vulnerability/lethality
VRM	-	Vulnerability reduction measures
WPAFB	-	Wright-Patterson Air Force Base

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As a result of recommendations made by the National Research Council to Mr. C. Adolph, OSD Director, Test and Evaluation (DT&E), in a report, "Vulnerability Assessment of Aircraft-A Review of the DOD LFT&E Program," Jan 93, an effort was launched to improve the live fire test (LFT) waiver process through development of a methodology to quantify advantages and disadvantages of full-scale, full-up test programs. Mr. Walter Hollis, the Army Deputy Under Secretary for Operations Research (DUSA[OR]), tasked the U.S. Army Materiel Systems Analysis Activity (AMSAA) and U.S. Army Research Laboratory (ARL) to develop the Live Fire Vulnerability/ Lethality Risk-Benefit Assessment Methodology. ARL (Deitz et al.) was chosen to lead this effort and AMSAA (LaGrange et al.) was to provide support. On 22 Mar 93, the set of proposed deliverables was accepted by Mr. Adolph and the Senior Test and Evaluation Group. This report presents a history and summarizes work done by the group. Section 2 discusses in detail the V/L process and methodology and models used in V/L assessments. Section 3 examines the connection of damage-to-engineering operations to processes different from standard V/L analyses. Section 4 discusses the type of survivability/ vulnerability information that must be developed during various phases of the acquisition cycle. Section 5 discusses four methodologies that could be applied to assess the cost-benefit LFT. Section 6 summarizes conclusions and recommendations. Appendices A-D provide details on the supporting theorems of section 4.

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